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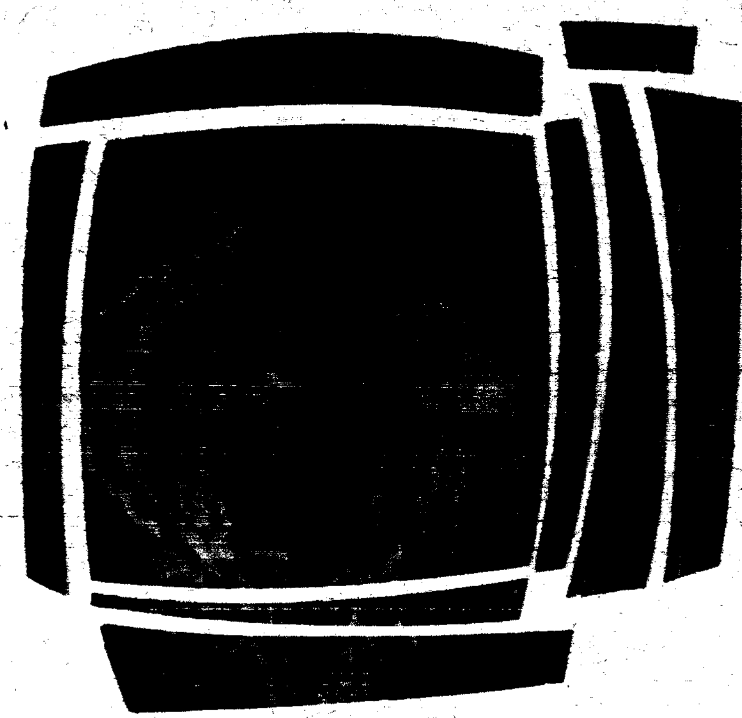

Interim Study for a Surveyor Lunar Roving Vehicle

FINAL TECHNICAL REPORT

BSR 1096

JPL CONTRACT

951057

Bendix SYSTEMS DIVISION

SURVEYOR
LUNAR ROVING VEHICLE,
INTERIM STUDY

FINAL TECHNICAL REPORT

BSR 1096

SUBMITTED TO

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

JPL CONTRACT
951057

1 FEBRUARY 1965

THE Bendix CORPORATION
BENDIX SYSTEMS DIVISION

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SECTION 1

INTRODUCTION AND SUMMARY OF RESULTS

This report documents work performed by the Bendix Systems Division under JPL Contract 951057, Interim Study for a Surveyor Lunar Roving Vehicle (SLRV). The purpose of the study was to investigate further parameters that affect earth-based control of the SLRV.

The program included the following tasks:

1. Investigation of the sensitivity of various parameters on the ability to control the SLRV remotely. These parameters include lunar illumination characteristics, optical sensor characteristics, ground displays, and display aids including path prediction.

2. Modification of the SLRV Phase I Engineering Test Model (ETM) to comply with the requirements of this study. The major modification consisted of installing a stereo TV system with associated pan and tilt mechanism.

3. Construction of a test course containing random obstacles, some within and others beyond the mobility capability of the ETM vehicle. The course was free from external references or position cues, and representative lunar illumination was used.

4. Conducting a test program to investigate various control parameters while driving the vehicle remotely over the test course. These parameters included the effect of step distance on safe traversal, accuracy with which obstacle dimension and location could be determined, decision time, and failure modes.

5. Study of the sensitivity of the navigational problem to the choice of control system parameters.

Previous reports completed on this contract include a Test Program Plan (BSR 1053) dated 1 December 1964, and an Interim Technical Progress Report (BSR 1059) dated 14 December 1964. Drawings and procedures generated during the performance of this contract are submitted separately with this report as well as a revision to the Phase I ETM Operation and Maintenance Manual (BSR 1097). Equipment required for the operational control system but not delivered under this study contract is listed in Appendix A.

1.1 PROBLEM DEFINITION

The problem of earth-based control of a lunar vehicle is mainly one of terrain assessment and path selection. The SLRV control problem is unique because the terrain is unknown and illumination conditions are unusual. The problem is further compounded by weight limitations and RF and circuit time delays.

Remote control through an RF link with a video display has been performed satisfactorily with aircraft and surface vehicles. However, such control was simplified because the operator was familiar with the vehicle and the terrain or medium over which the vehicle was being controlled. For example, a pilot remotely controlling an aircraft has the advantage of years of experience flying aircraft with similar performance characteristics. Also, since the operating medium is well defined, curves of performance vs speed or attitude can be constructed. The SLRV operator has no such advantages.

1.2 MISSION REQUIREMENTS

The requirements of the study included determining the sensitivity of certain parameters to remote control and selecting design points for these parameters based on a 150-lb vehicle weight. Therefore a 150-lb SLRV and mission must be defined.

The basic 100-lb SLRV resulting from the Bendix Phase I Study is shown in Figure 1-1. The mode of operation is to transmit slow-scan TV pictures for terrain evaluation. Following picture evaluation the SLRV is commanded to move a certain step length. After this step the parabolic antenna must reacquire the earth and the SLRV is commanded to take a new series of TV frames. TV data cannot be obtained while the SLRV is in motion. During the Phase I study a 150-lb vehicle was also defined as having the following additional design features:

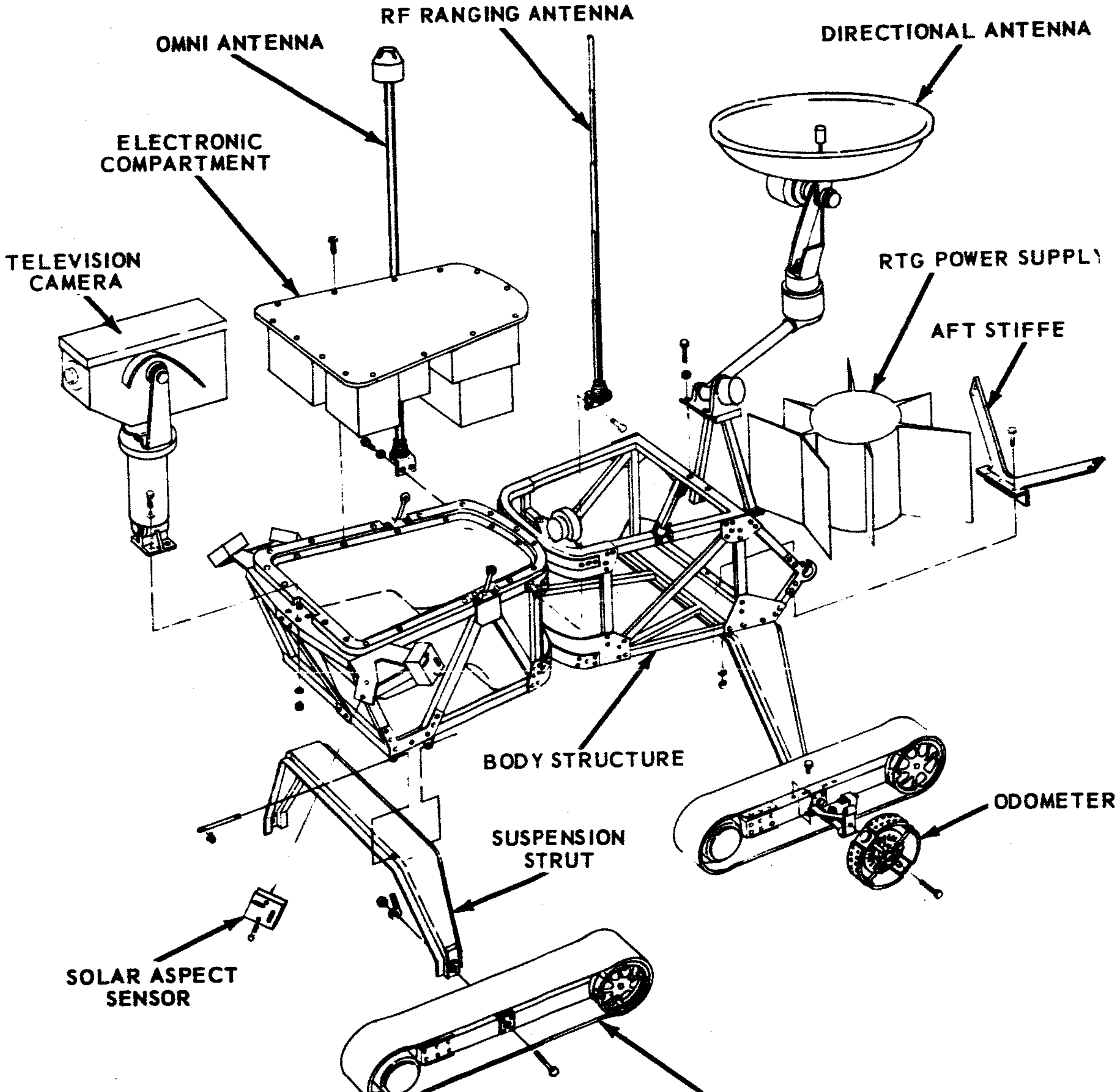


Figure 1-1 SLRV 100-lb Configuration

1. Greater electrical power

2. Greater mobility

3. Stereo TV system

4. Redundancy

The mission requirement of the SLRV system is to verify that lunar landing sites meet LEM requirements. The Phase I study showed that this requirement could be met if 19 points, each 40 meters in diameter, could be verified as acceptable within a 3200-meter-diameter landing site. A landing site is shown in Figure 1-2 with the landing points shown approximately 500 meters apart.

In addition, each 40-meter-diameter point was to be surveyed in the prescribed pattern, as shown in Figure 1-3. Five monocular TV pictures are taken at 187 locations within a point; the vehicle step length is 3 meters, resulting in an intrapoint travel distance of 558 meters. This mission profile was considered the basis for determining control parameter sensitivity.

The Phase I study divided mission time as follows:

Mission Function	Percent of Mission Time
Travel time	20.1
Penetronometer	5.9
TV camera slew	9.3
TV transmission	8.7
Antenna slew	1.2
Mission decision time	54.8
	100.0

Although the elements of mission time are somewhat interdependent, mission decision time has the most profound effect on total mission time. Mission decision time is composed of the following elements:

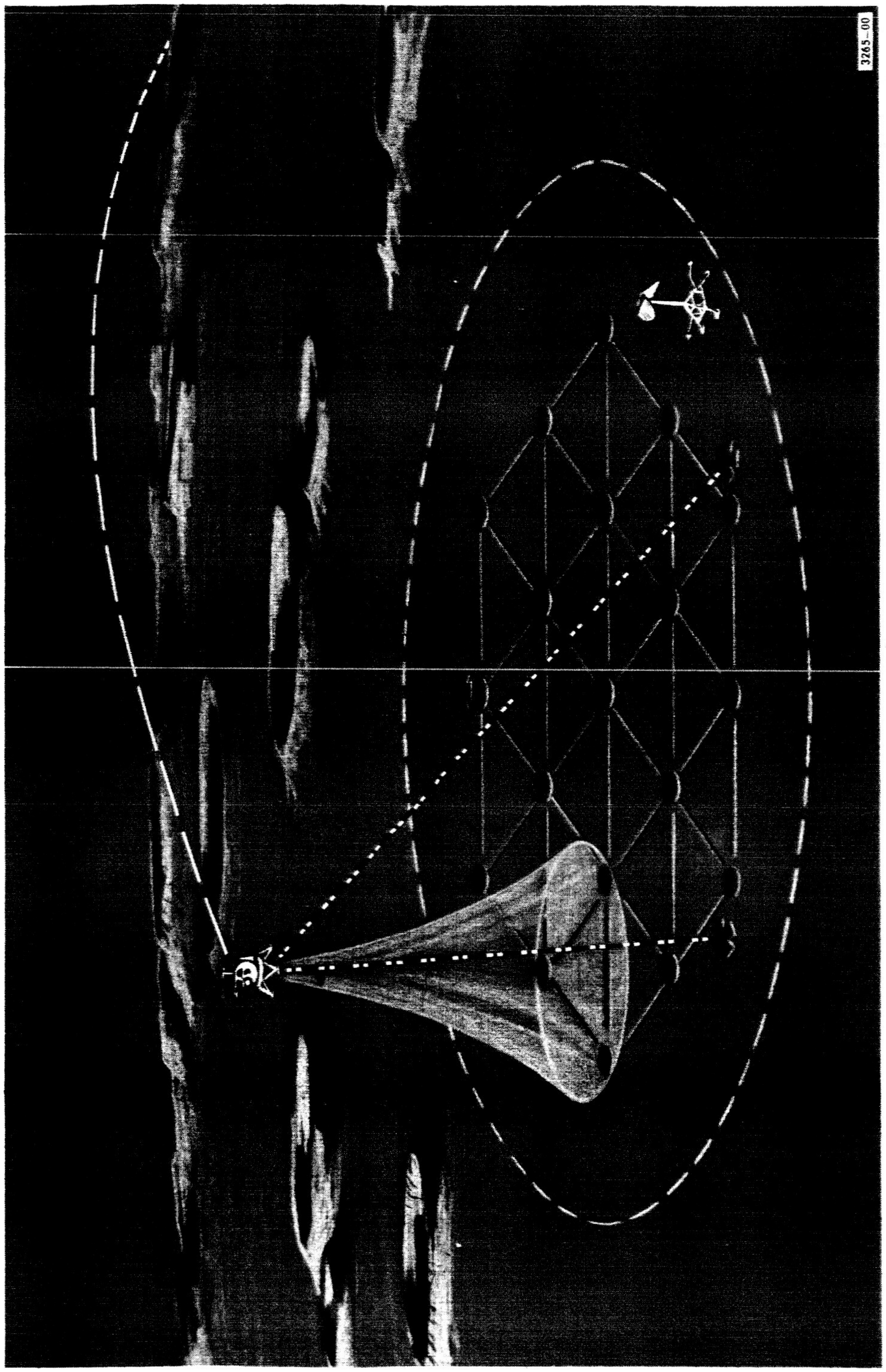


Figure 1-2 LEM Landing Site Certification Geometry

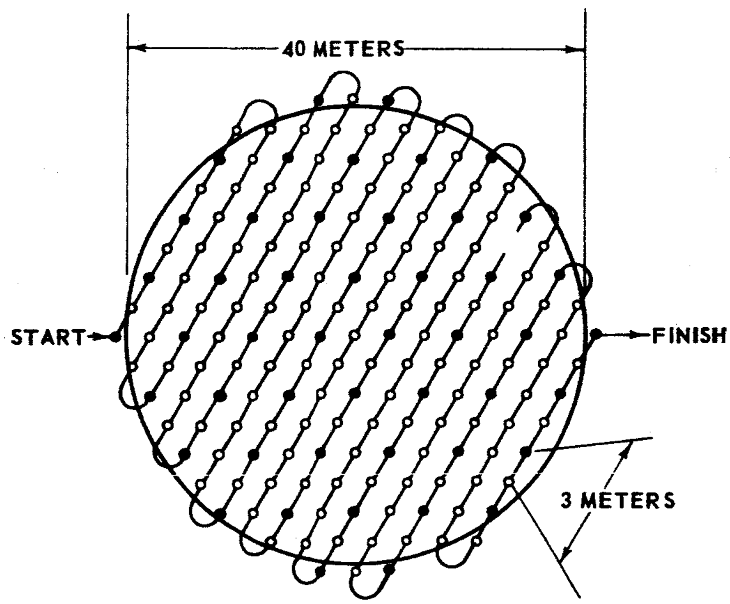


Figure 1-3 Point Survey Pattern

(a) Display generation time

(b) Operator display evaluation time

(c) Number of TV display frames per step

(d) Command formatting and transmission time

(e) Number of steps per mission.

Since TV pictures are taken at each step, items (c) and (e) must be multiplied by the other elements of decision time. This relationship can be expressed as:

$$\text{Decision time} = \left[a + b + d\right] (c) (e)$$

Since (a) and (d) are hardware implementation problems, they are assumed constant for this study. The objective can thus be stated as minimizing the product (c) (e) [constant + b], and the sensitive elements affecting mission time can be defined as:

1. Number of steps

2. Terrain assessment time

3. Number of TV pictures per step.

These factors were evaluated most critically during the study. Several parameters were listed for study in the work statement. The effect of these parameters on the above elements of mission decision time was emphasized during the study. For example, field of view affects the number of TV pictures required.

1.3 STUDY APPROACH

Throughout the developmental tests and vehicle test program worst-case operating conditions were assumed. Essentially all of the test course terrain was classified as rough to isolate the most significant control problems under operating conditions believed to be marginal. It is believed that a smoother test course would result in better vehicle performance and less dispersion in terrain assessment accuracy but a poorer understanding of possible remote control problems.

The TV performance is based on a vidicon sensor. If greater sensor sensitivity, resolution, or dynamic range is possible, the test results certainly would either remain constant or improve. The generation of stereo TV during the vehicle test program by use of a color anaglyph was an expedient for this study.

Also, a single vehicle configuration and vehicular operating mode was used throughout the test program. The operating mode involved a minimum amount of vehicle instrumentation and operator display. It was assumed that the operator's performance could only improve with additional, properly selected instrumentation and display aids.

The study was divided into several tasks performed either in parallel or in sequence. Initial tasks were performed without the aid of the large test course, modified ETM, or color anaglyph stereo TV systems. The program was divided into the following elements.

1.3.1 Developmental Tests

The developments tests were designed to analyze all control parameters not requiring the vehicle to be driven on the test course. More control was maintained over these parameters in an office or the photometric laboratory than could be maintained on a test course. These tests included the following.

1.3.1.1 Surface Assessment Experiments

The surface assessment experiments investigated the degree to which several test subjects could assess terrain features. Twelve test subjects made quantitative judgements of terrain features from photographs taken of a representative lunar terrain. The photographs were taken of a TV monitor showing both monocular images and stereo pairs with different baselines. The effect of different lighting conditions and overlay grids on performance was also measured.

1.3.1.2 Transmission Degradations

The effect of reduced signal-to-noise ratio (S/N) in the video display was measured to determine the effect of reduced communication performance. The tests used a stereo TV system and measured the degradation in stereo acuity with reduced S/N.

1.3.1.3 Surface Lighting

The surface lighting experiment evaluated photographs of two representative lunar terrain models under different lighting incident angles. The TV gray scale coding was also varied to determine its effect on terrain assessment. Test subjects made subjective judgements of the photographs and rated the adequacy of data presentation.

1.3.1.4 Path Prediction

The value of path prediction data was evaluated by several trained operators using the COED (Computer Operated Electronic Display). A detail discussion of the developmental tests and results is contained in Section 3.

1.3.2 ETM and Console Modification

The ETM vehicle delivered to JPL under the Phase I contract was returned to Bendix with the control consoles. Modifications were made to the ETM and console for use in the remote control study. The most significant change was the addition of the stereo TV camera and a camera pan and tilt servo mechanism. A detailed discussion of the vehicle modifications is contained in Section 2.3.

1.3.3 Test Course Preparation

The work statement required the use of a test course containing large random obstacles and no external position cues. Representative lunar lighting was necessary. Therefore, a large open area with high overhead clearance was required. A bay of an aircraft maintenance hangar at Willow Run Airport near Ann Arbor, Michigan, was used. This permitted the design of a 60 x 60 ft test course, which was believed to be the minimum size for this program. A discussion of the test course facility is contained in Section 2.4.

1.3.4 Vehicle Test Program

The vehicle test program was designed to determine an operator's performance in remote driving of the vehicle on the test course. Tests were conducted as follows.

1.3.4.1 Vehicle Calibration Test

The vehicle was calibrated to determine its mobility performance on fixed obstacles. These measurements were made adjacent to the test course and included static stability tests, turning characteristics, and crevice crossing capability. Similar tests were performed on the test course with the intended remote control operators directly observing the vehicle responses to aid in developing operator proficiency.

1.3.4.2 Vehicle Configuration Tests

The vehicle configuration tests were designed to fix vehicle parameters prior to the performance evaluation tests on the test course so that the number of variables could be reduced. The tests resulted in the selection of the following design points:

1. TV camera position
2. TV camera field of view
3. TV stereo baseline

1.3.4.3 Performance Evaluation Tests

The performance evaluation tests studied an operator's ability to remotely control a vehicle on the test course. The mode of operation was similar to that proposed in Phase I; that is, discontinuous or step driving with TV data available only when the vehicle is stationary. Parameters evaluated included:

1. Decision time
2. Step lengths
3. Stereo performance
4. Effect of illumination condition
5. Failure modes

A detailed discussion and test results of the vehicle test program is contained in Section 2.

1.3.5 Navigation Compatibility

An analysis was made of the interface between navigation and control. The navigational requirements determined in the Phase I study were used as a baseline for performance requirements. A discussion of these results is contained in Section 5.

1.3.6 Ground Display and Control

The requirement for many display and control features became evident during the study. A discussion of these techniques is contained in Section 4.

1.4 SUMMARY OF RESULTS

The study results are based on a combination of the following tasks:

1. The developmental tests conducted by computer simulation tests or by surface assessment tests in a laboratory without the ETM vehicle

2. The performance evaluation tests where operators were required to drive the ETM remotely across the test course.

It was expected that the quantitative data on accuracy of surface assessment obtained during the developmental tests would correlate with the remote control performance tests on the test course. Such was not the case. The developmental tests indicated wide dispersion in the accuracy of surface assessment judgements such as size and distance to obstacles. However, when the operators were required to drive over such terrain, their performance exceeded that predicted from the surface assessment experiments. A possible explanation is that the operators evaluated the rough random terrain not on the basis of individual judgement of size and distance, but rather on the basis of overall terrain contour profile. They thought the task was part art, part science. Likewise, the quantitative data comparing stereo to monocular assessment indicated only a slight advantage for stereo. However, during the vehicle test program the operator expressed a definite preference for stereo. Study results are summarized as follows:

1. Generally control failures did not result from inability to recognize gross hazards such as excessive slopes, undercarriage clearance, or other obstacles approaching the vehicle's calibrated mobility values. Rather, failures resulted from hazards which caused one or more traction units to stall, such as wedging between two rocks, each of which was well within the obstacle crossing capability of the vehicle. Changing the vehicle's path an inch would frequencly remove the hazard. Such features indicate areas where greatest mobility emphasis should be placed.

2. Numerical safety factors can be assigned but cannot be applied to rough areas of a random test course where terrain is essentially N-dimensional; the vehicle's performance must be measured against the spatial relationship of many features and obstacles.

3. Remote control of a vehicle over random terrain approaching and sometimes exceeding the mobility capability of the SLRV is not feasible as a normal means of operation, but rather only to traverse locally rough areas.

4. The remote control of an SLRV requires control aids in addition to a basic stereo display and vehicle attitude sensor when operating in a rough terrain. These aids may be in the form of mechanical safety devices or optical measurement improvement device such as photogrammetric ranging aids.

5. The operation of the ETM on a test course approaching and in certain areas exceeding vehicle mobility, although tedious, resulted in few catastrophic failures. The conclusion is drawn that if the lunar terrain is less rough than the test course there will be a high confidence in mission success.

6. Quantitative measurement indicated only a slight advantage for stereo display; the advantage was more apparent on rough terrain. Throughout the test program the operators thought that stereo was desirable for terrain assessment and that they could better interpret overall scene geometry with a stereo display. An interocular stereo baseline was preferred for ease of viewing. Where accurate objective measurements of surface geometry are required, this baseline is inadequate.

7. The dispersion in size and distance judgements through either a stereo or monocular display was approximately three times greater than that with direct viewing. This indicates considerable room for improvement through more effective image display, training, and experience.

8. An optical sensor with a field of view of 70° or greater is recommended. Generally it is not necessary to show the extremities of the vehicle in the display, if their position with respect to scene geometry is known to the operator. The optimum optical sensor location may not be the highest position above the terrain, as was anticipated. Of the several positions used during the program a lower height located back from the front of the vehicle was preferred.

9. Frequently operators requested multiple TV pictures before completing terrain assessment. A mosaic display presentation and/or rapid video data retrieval is recommended. The grey level rendition and resolution of a vidicon was satisfactory.

10. An odometer and heading and steering angle sensors are required on the vehicle. These sensors make possible closed-loop driving where step distance and/or direction changes are made without stopping the vehicle to take a new sequence of pictures. The advantage of closed-loop driving and a path prediction aid was apparent during the COED computer simulation testing.

SECTION 2

ETM TEST PROGRAM

Worst-case test conditions were selected for evaluating ETM remote control performance. A rough test course was constructed that was largely equal to or exceeded the vehicle's mobility capability. This allowed a better definition of problem areas. The vehicle operating mode was open-loop without path prediction. Program limitations precluded the possibility of closed-loop operation or predictive aids. It is important to consider these adverse test conditions in interpreting the results.

2.1 ETM TEST OBJECTIVES

The ETM test program was designed to complement the development test program. Only those effects which could not be studied individually or at another location were included in the test program. The ETM program was restricted to remotely controlling the vehicle in a simulated environment and under simulated mission conditions.

The objectives of the ETM test program were:

1. To verify feasibility of remote control - The feasibility of remotely controlling a vehicle across the simulated lunar terrain was to be demonstrated.

2. To extend results of development tasks - The ETM test program was designed to extend the results of certain portions of the development tests to an actual physical simulation. In particular, such test results as metric evaluations, stereo baseline evaluations, and COED experimental results were to be considered.

3. To evaluate parametric effects - The effect of certain parameters upon the remote control performance was to be evaluated. The vehicle operating mode, terrain characteristics, TV sensor parameters, display aids, and illumination angles were the primary parameters to be studied. The basis of comparison for remote control performance was the average vehicle velocity, decision time, step length, and failure modes.

4. To define major problem areas further - The ETM test program was designed to advance significantly the understanding of major problems in remotely controlling the vehicle. Of primary concern were the problems as surface assessment, safety factors, failure modes, and ground control console-display design features.

2.2 TEST RESULTS AND DATA

2.2.1 Surface Assessment Accuracy

A series of tests was performed to allow comparison of metric judgement accuracies as determined by the development tests and the ETM tests, using the color anaglyph stereo display system. A second objective in performing these tests was to establish to the operator through an experimental training procedure the relative geometry of the vehicle and camera positions, vehicle tracks, and the viewed scene.

Three test subjects were used for these tests. The vehicle operator, to be responsible for surface assessment and the actual driving procedures, was selected on the basis of the developmental test performance. The vehicle driver was selected on the basis of developmental test performance and previous experience in driving the vehicle. The third subject was selected on the basis of stereo perception and to provide further comparison of individual performances.

The following procedure was used. The vehicle was located at some arbitrary point in the test course. The cameras were covered so that no picture was available on the TV monitor, prohibiting the observation of any possible cues by the test subjects. After pointing the cameras at a preselected standard angle, the cameras were uncovered, allowing the viewed scene to be presented on the TV monitor. The test subjects mutually selected three conspicuous rocks, arranged in three estimated distance categories: zero to 6 ft, 6 to 12 ft, and 12 to 18 ft. Each test subject then recorded on a standard data sheet his own estimate of the size and distance of each rock in question. This was done without consulting the other test subjects. When all estimates were complete, the actual sizes and distances of the rocks were measured and recorded on the same data sheets.

The measurement accuracy performance of the three test subjects is summarized in Table 2-1. The performance of the vehicle operator (Subject 2) was better in the development tests than for the anaglyph stereo performance. However, the performance of the vehicle driver (Subject 3) improved from the development tests to the ETM tests in which the anaglyph stereo television display was used. These results can be seen in the comparison of these standard deviations for the size and distance estimates. The net result is that the performance of the two subjects during the ETM test program was essentially identical. The third subject (Subject 1) did not participate in the development test, since he helped in all portions of the experiment design.

TABLE 2-1

SURFACE ASSESSMENT PERFORMANCE SUMMARY

DEVELOPMENT TESTS				
Subject	Size, Inches		Distance, Inches	
	$\bar{x}$	σ	$\bar{x}$	σ
2	-2.9	6.7	-0.7	14.4
3	-0.4	9.3	-0.2	34.5
ETM TESTS				
Subject	Size, Inches		Distance, Inches	
	$\bar{x}$	σ	$\bar{x}$	σ
1	1.3	7.6	-6.9	22.3
2	1.3	4.8	2.2	26.4
3	0.2	4.9	5.0	25.3

From the performance of these three test subjects for the anaglyph stereo television system used in the ETM tests, the following comments can be made. Performance of the three test subjects was very closely grouped. The size estimates were marked by low mean error and by a standard deviation of approximately 5 inches. The primary descriptor of performance is the standard deviation; the mean is valuable only in establishing the tendency to overestimate or underestimate metric dimensions. This standard deviation indicates that errors in size estimates are not particularly well grouped, but tend to range over a considerable spread. It should be noted that the distribution of errors in all tests was not examined for normality. Thus, although the standard deviation is useful as an indication of dispersion of errors about the mean, it does not necessarily imply the conventional percentages associated with a normally distributed population. The distance estimates using the anaglyph stereo television display also seem to be rather consistent for the three test subjects. Subject 2 indicated a tendency to underestimate distances, while the other two subjects tended to overestimate distances, as indicated by the mean scores. All three subjects had a standard deviation of distance errors of about 25 inches. Again, the comments regarding the significance of the standard deviation noted above should be kept in mind.

A similar test of estimating object sizes and distance was performed for a monocular television system. The procedure for this test was similar to that described above, except that the anaglyph stereo display was modified to present a monocular picture. Table 2-2 presents results of the size and distance estimates for stereo and monocular display systems. In brief, there does not appear to be a significant difference in performance between stereo and monocular television systems for the task of absolute distance estimates. In general, this result was anticipated, as indicated by the development test results.

Table 2-2 shows that there is a slight improvement for monocular viewing over stereoscopic viewing. This is attributed primarily to learning; the monocular tests were performed after the subjects had become accustomed to the display. This learning process however is reflected in the stereo performance scores, which include measurement data from the very outset of the tests. The results of Table 2-2 are not believed to disprove the value of stereo viewing. Although stereo viewing does not appear to provide a significant improvement in absolute metric judgements, it does provide a far superior picture for general surface assessment. All subjects agreed strongly on this point. In particular, the monocular presentation lacked the detail present in the stereo picture. Several of the objects selected by the test subjects in the monocular series of tests were actually portions of one rock, two rocks, or in one case, simply an irregular lump on the ground, rather than single discrete rocks. This lack of picture definition is believed to hamper seriously fine scale surface assessment.

TABLE 2-2

ETM SURFACE ASSESSMENT TEST RESULTS

MONOCULAR TESTS				
Subject	Size, Inches		Distance, Inches	
	$\bar{x}$	σ	$\bar{x}$	σ
2	2.3	3.8	10.5	22.3
3	2.5	3.1	-3.7	23.6

STEREO TESTS				
Subject	Size, Inches		Distance, Inches	
	$\bar{x}$	σ	$\bar{x}$	σ
1	1.3	7.6	-6.9	22.3
2	1.3	4.8	2.2	26.4
3	0.2	4.9	5.0	25.3

The results of the monocular-stereo viewing test comparisons and comparison of control performance for monocular and stereo operation do present one interesting possibility. Stereo viewing may not be necessary in conditions where the surface is quite level and featureless. In this situation, stereo television would not appear to offer any advantages. Thus, it would appear desirable to provide flexibility in the system to allow operation with a monocular picture if the surface conditions are suitable.

As a further means of comparison, the size and distance estimation performance for stereo viewing was compared with that for viewing the scene with the naked eye. This comparison was thought to be necessary; obviously, the test subjects could not be expected to perform better with a stereo television system than they could with their natural facilities. The procedure for this test was quite simple. The subject simply selected locations on the test course at random from which estimates were made on rocks in the three range categories. Table 2-3 summarizes the results. In general, performance with the naked eye was approximately three times more accurate than that with the stereo television display. This wide separation was expected. The scores provided through the visual tests would appear to be the upper limit on performance to be expected for any display system. That is, the best feasible display system with the most aid to the operator will provide performance which may approach that achieved with the naked eye, when subjective evaluations are used.

TABLE 2-3

ETM SURFACE ASSESSMENT VISUAL-STEREO PERFORMANCE

VISUAL TESTS				
	Size, Inches		Distance, Inches	
Subject	$\bar{x}$	σ	$\bar{x}$	σ
2	0.4	1.7	0.6	10.0

ETM STEREO TESTS				
	Size, Inches		Distance, Inches	
Subject	$\bar{x}$	σ	$\bar{x}$	σ
2	1.3	4.8	2.2	26.4

As a means of further evaluating the performance of the subjects for the three test conditions (monocular viewing, stereo viewing, and viewing with the naked eye), the size and distance estimates were partitioned as a function of range to determine the variation in performance as a function of range. The results are summarized on Figures 2-1, 2-2, and 2-3. Figure 2-1 presents the size estimation performance. In general, the mean error in size estimates was approximately the same for all three cases. It should be noted that no data points are available for monocular viewing in the 12 to 18 ft range category. This discrepancy is explained

Figure 2-1

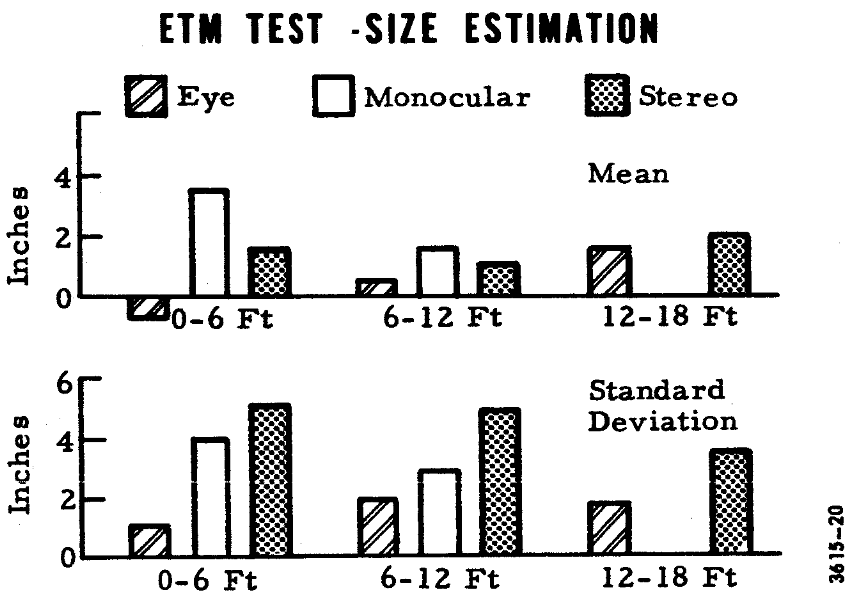

ETM TEST -SIZE ESTIMATION
Eye
Monocular
Stereo
Mean
Inches
4
2
0
0-6 Ft
6-12 Ft
12-18 Ft
6
Standard
Deviation
Inches
4
2
0
0-6 Ft
6-12 Ft
12-18 Ft
3615-20

Figure 2-2

ETM TEST DISTANCE ESTIMATION-MEAN

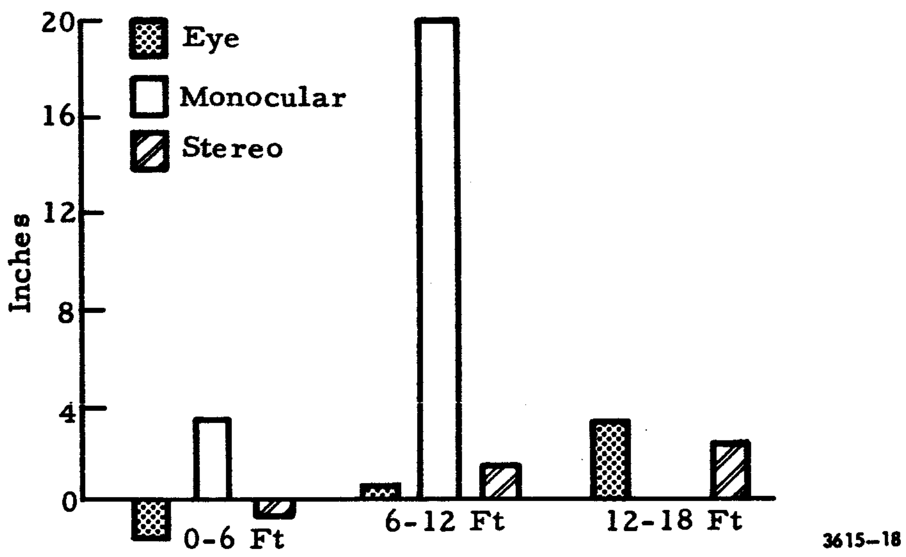
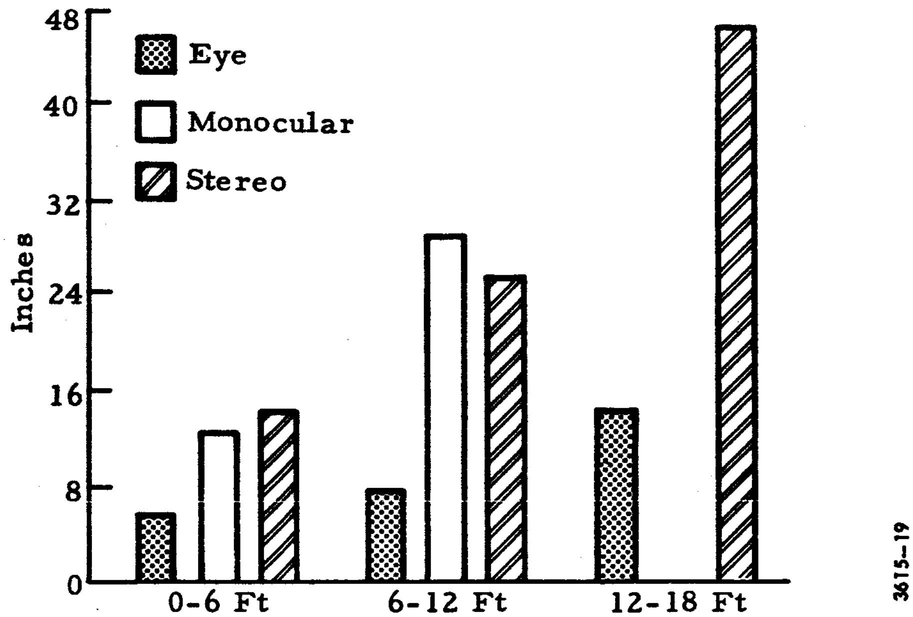


Figure 2-3

ETM TEST DISTANCE ESTIMATION-STANDARD DEVIATION



below. The standard deviation of size estimate errors in general is not particularly enlightening. Performance with the naked eye appears to be rather independent of range. Performance for monocular and stereo television seems to improve with range; this is contrary to expected trends. Figure 2-2 provides the distance estimation mean for the three viewing modes. As can be seen, the mean for monocular viewing in the 6 to 12 ft category is surprisingly high, which indicates the tendency for gross overestimation of the distance to obstacles in that range category. The extreme tendency to overestimate distances resulted in no data points being obtained for monocular viewing in the 12 to 18 ft category. Subjects erroneously thought they were selecting objects in the 12 to 18 ft category. However, they were in actuality selecting obstacles in the 6 to 12 ft range category and grossly overestimating the ranges to these obstacles. This provides a further indication of the preference for stereo viewing as opposed to monocular viewing. This tendency was not noticed with stereo viewing. Performance for the other two viewing modes appears to be rather well behaved.

Figure 2-3 compares the standard deviation of distance estimates for the three cases. Performance with the eye did tend to decrease with with increasing range, as was expected. This is evidenced by the increase in error dispersion with range. This was also true for stereo viewing and appears to be true for monocular viewing for the two cases considered. It is expected that the standard deviation for monocular viewing in the 12 to 18 ft category would exceed that for stereo viewing, again substantiating the preference for stereo viewing.

In summary, the ETM measurement accuracy tests provided the following results. There was no clear-cut preference between stereo and monocular viewing. When the data were partitioned as a function of range, a definite tendency for misjudging distances as a function of range was indicated for monocular viewing. Thus, for rough irregular surfaces, stereo viewing is the preferred mode. If the surface is rather plain and featureless, it would appear that monocular viewing is sufficient. The ability to estimate sizes and distances is not particularly accurate. Consequently, difficulty was anticipated in controlling the vehicle in the test course terrain.

The role of metric judgements in surface assessment is not clear. In general, surface assessment is not characterized by a painstaking metric judgement of every feature in the field of view. Rather, the entire scene is surveyed as a whole. Without doubt, the ability to judge the size and distance of isolated features is essential to the roll of surface assessment. Ability to achieve accurate distance estimates is also necessary in selecting paths and step lengths. The metric judgements of the operators serve as a fundamental reference in the overall evaluation of the viewed scene.

2.2.2 Operator Decision Time

One of the easiest and most direct means of evaluating remote control performance is by measurement of operator decision time. Operator decision time refers to that time period required by the operator to evaluate all pictures he may need in assessing the surface before committing the vehicle to motion. This parameter does not include time factors for such functions as antenna or TV camera slewing, communications transfers, or command generation time. Since a long operator decision time reduces average vehicle velocity, it is desirable to reduce decision time to the lowest possible value.

To simplify the problem as much as possible, all factors related to strategy decisions were kept at a minimum. The term "strategy" as used here denotes the long-term decisions required by the operator when remotely controlling the vehicle. A typical example is the general path to be followed in reaching a desired destination. Often, the best route to the desired goal is not necessarily along a straight-line path. By selecting an easier alternate route, the operator can often reach the desired goal in a shorter period than by the straight-path route. Since the study of strategy decisions was outside the scope of the program, the selected test run allowed the desired goal to be reached in a rather direct fashion.

The method of data collection was straightforward. At each stopping point along the path, the operator could request as many pictures as desired. The total time spent by the operator in studying the picture, from the presentation of the picture until the operator announced his intended step or requested a new picture, was measured and recorded as decision time. No other time factors were included in this performance parameter.

Figure 2-4 shows the frequency distribution of decision time intervals. As can be seen, decision times of 11 to 20 and 21 to 32 seconds are the most prominent. The distribution is fairly flat out to about two minutes decision time. Beyond this, the frequency of occurrence diminishes

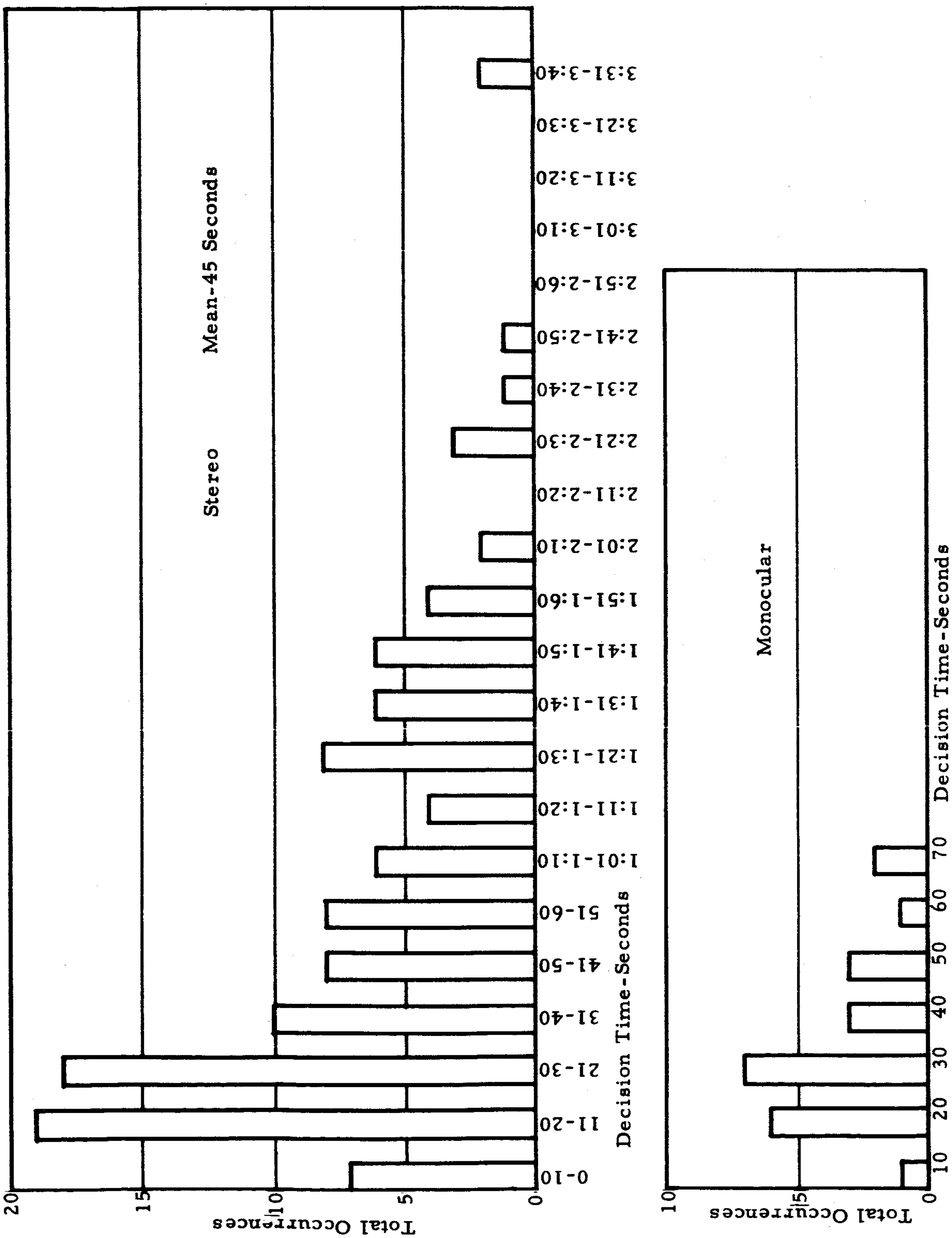


Figure 2-4 Decision Time Data

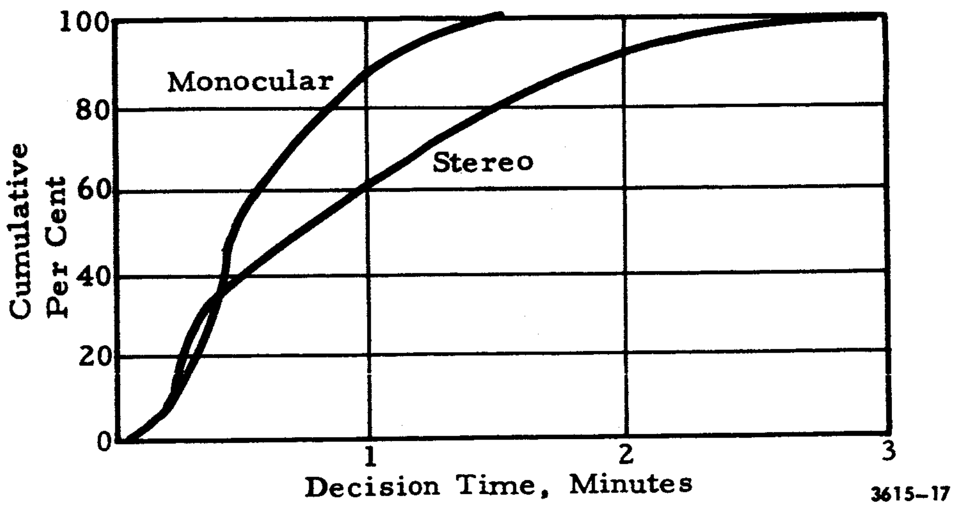
rapidly. These data include the learning process, in that data from the very outset of the tests are included in the total. A very definite learning process was exhibited. By plotting the decision time as a function of time (experiment duration), it was evident that both the average value of decision time and range of excursions decreased as a function of time. Plotted for comparison below the main distribution of decision time is the similar distribution for monocular TV performance. The amount of data obtained for monocular performance is rather limited. Therefore, any conclusions drawn solely for monocular performance must be subject to verification with more extensive data. However, monocular performance would appear to be equivalent to stereo performance.

Figure 2-5 represents the accumulated decision time data for monocular and stereo performance. For stereo performance, 50% of all decisions were made within 45 seconds and 90% within 2 minutes. For monocular performance, 50% of all decisions were made within approximately 25 seconds and 90% within approximately 1 minute 5 seconds. A comparison of these results indicates that monocular performance is superior to that of stereo. Several factors act to minimize the difference. First, as mentioned, the stereo performance includes a significant learning process; the monocular tests, which followed the stereo tests, gained the advantage of this learning process. It is expected that as further data are gathered for stereo performance, the curve would fill out more in the 20 second to 2 minute category, approaching the monocular curve. Limited data also render the monocular curve somewhat sketchy. One other factor must be considered. The monocular picture, which contained less picture detail than the stereo picture, presented less information for the operators to evaluate. Consequently, evaluation and assessment of the terrain as seen by the pictures represents a more gross decision and therefore could be made more quickly. It is expected that this distinction will always exist between the two display modes.

The importance of operator decision time in the makeup of the entire mission must be considered carefully. Again, it should be noted that operator decision time as used here implies only the time necessary to evaluate pictures for terrain assessment purposes. The term "decision time" as has been more commonly used implies the total elapsed time at each vehicle stopping position. In Section 1.1 a time percentage breakdown for a 100-lb vehicle mission is presented. It can be seen that the total time spent at each vehicle stopping place represents over half of the total mission time. As such, this time factor represents the most sensitive

Figure 2-5

ACCUMULATED DECISION TIME DATA



parameter in the vehicle design. The actual operator decision time represents about 12% of the total decision time or about 6.6% of total mission time. Therefore, to reduce total mission time, it is desirable to reduce the operator decision time. The methods for accomplishing this are discussed in more detail in other portions of this report. Briefly, they are: efficient data display at the ground control console, a picture recall capability of previous pictures, thorough knowledge of the vehicle behavior by the operator, and thorough training of the operator before the actual mission. These factors cannot be overemphasized.

The time values obtained in the ETM test program are thought to be a rather close approximation of those of the actual mission. Several restrictions in the test procedure would tend to increase the picture assessment time beyond that of the actual case. Operation of the vehicle in the ETM test program was in an open-loop fashion without the benefit of prediction. The absence of these aids acts to increase the time required for the operator to formulate decisions. However, the test program did not place on the operator the tremendous emotional pressure that will exist in the actual mission. This intangible factor would tend to increase the time required for the operator to formulate his decision. It is estimated these two contradictory tendencies would in general negate each other, rendering the test results a good approximation of the ultimate situation.

2.2.3 Step Length

The step length is defined as the effective distance the operator elects to move the vehicle in each driving operation. Only the absolute value of the step is considered; forward or reverse directions are not relevant. The measurement of this factor in the test program was straightforward. Once the operator had formulated his decision, he announced the intended step maneuver and the intended distance. A perfect odometer was assumed. That is, the experiment personnel on the test course maintained power to the vehicle and measured vehicle progress until the desired step length was achieved. One special point should be noted here. At certain times throughout the mission, the operator elected to crimp the vehicle before initiating a turn condition. This procedure was adopted to effect a maximum turn without requiring the vehicle to go through a steering transient before reaching the maximum turn condition. A crimping operation was scored in the test as a step of zero length, since the vehicle effectively did not move in this operation.

Figure 2-6 represents the frequency distribution of step length for the test program. It can be seen that a large number of steps occurred in the 0 ft category (crimp procedure). Considering all steps of positive movement, the data appear to be symmetrically distributed about a mean step length of 4 ft. The maximum step attempted was 8 ft; the minimum, other than the crimp turn, was a 1-ft step. Included on the same figure are the frequency of occurrences of steps for monocular driving. Again, much less data are available for monocular driving performance.

Figure 2-7 illustrates the cumulative number of step lengths in the various categories. Considering driving with a stereo display, about 20% of the total steps are accounted for by crimp maneuvers. Fifty percent of all steps are 3 ft or less in length and 90% are approximately 5 ft or less in length. For stereo display driving without crimp turns, 50% of all steps are about 3. 5 ft in length or less and 90% of all steps are less than about 5. 5 ft. In comparing this case with that of monocular display performance, it can be seen that little difference exists. The curve for monocular driving appears somewhat irregular; this is probably due to the limited number of data points considered. In summary, it can be said that little difference exists in the step lengths for stereo or monocular driving.

It is important to note that the above data were derived for operation on the test course, a very rough surface which largely equals or exceeds the vehicle's mobility capability. As such, the data represent the worst practical operating conditions. The resultant step lengths therefore represent the minimum anticipated values. As surface roughness decreases, the average step length will increase. As an example, the average step length on the COED simulations for closed-loop control with prediction was nearly 15 feet.

In considering the failure modes observed in the past operations, a total of six failures resulting from control errors were observed in 120 steps attempted. A failure is defined as the inability of the vehicle to continue forward motion. Thus, a failure does not necessarily imply complete immobility of the vehicle. One of these six control error failures was committed by attempting to scuff-turn the vehicle on a rocky surface. This maneuver should not be attempted on irregular random surfaces. The remaining five failures were all the direct result of improper step lengths. In each case, the operator attempted to drive the vehicle further than was called for in the situation. As a direct result, the vehicle was driven off

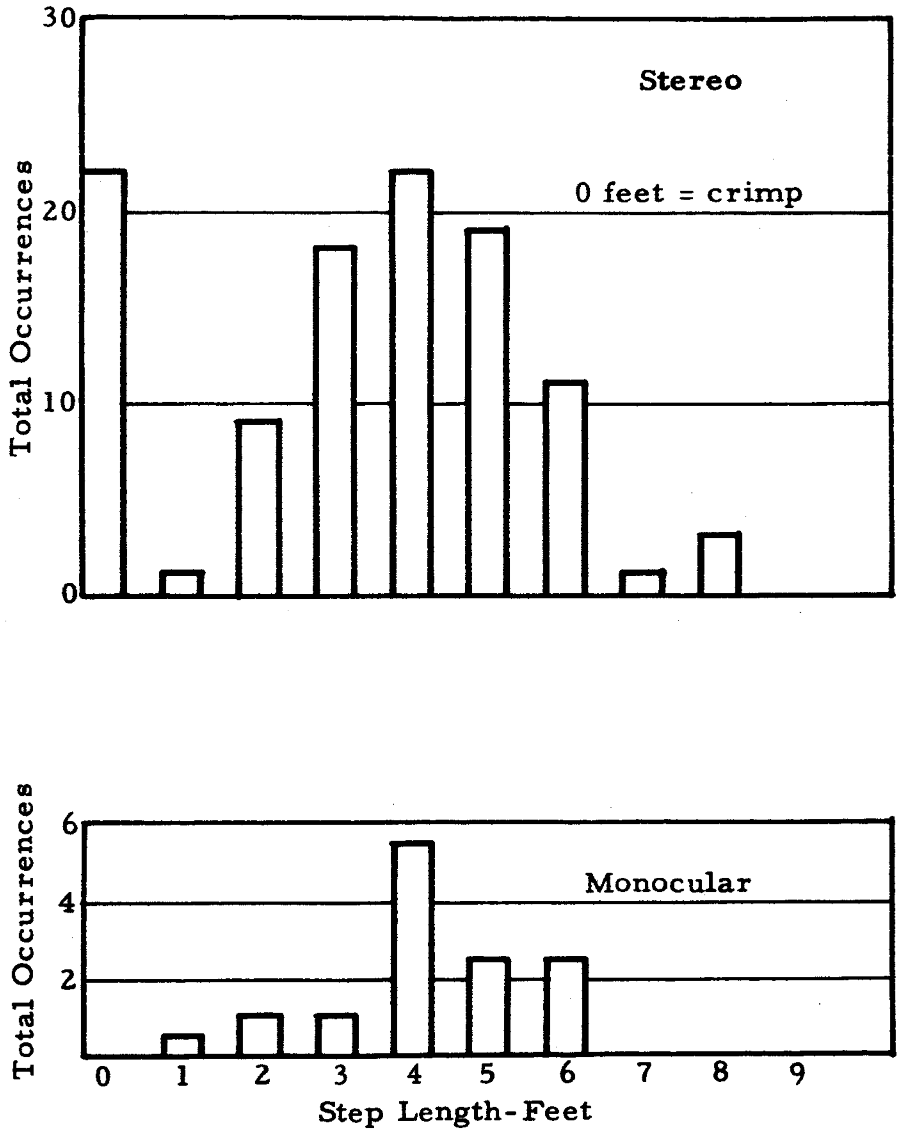
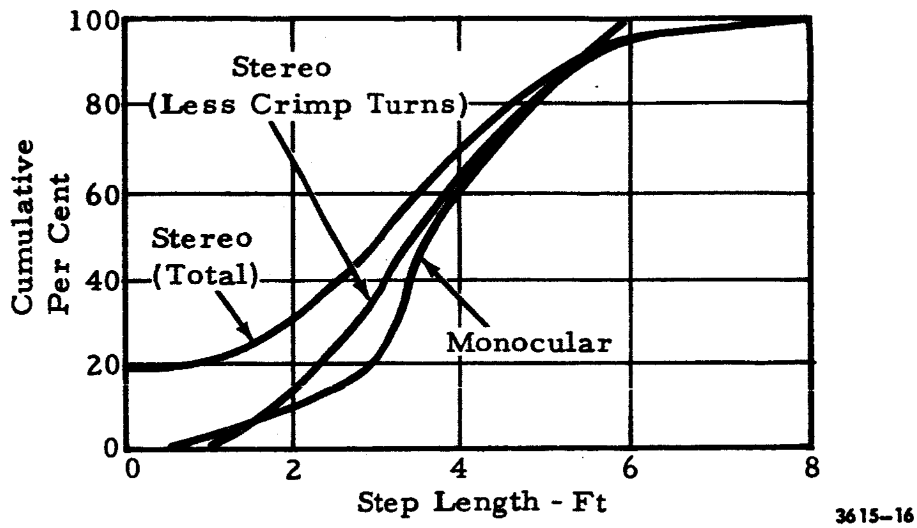


Figure 2-6 Step Length Data

Figure 2-7

ACCUMULATED STEP LENGTH DATA



the intended path into an undesirable area, ultimately resulting in a scored failure. For these failures, steps 4 ft or greater were called for. In both cases in which 8 ft steps were attempted, failures ultimately resulted. The importance of correctly determining the proper step length becomes apparent and emphasizes the requirement to estimate accurately distances to specific objects and the viewed scene. Too few total failures were experienced to allow a correlation of failure rate to step length. It is believed that more data would establish a strong correlation between the two. Additional data are required to establish the actual relationship more closely.

The ETM test results would seem to indicate that short steps (1 to 3 meters) can be expected as the normal operating mode. This result in itself is quite significant. During the Phase I design program, step length was treated as a dependent variable, primarily as a function of TV resolution. However, it appears from the test program that step length should be treated as an independent variable not directly related to TV resolution. A number of other factors influence the proper step length selection. First are the surface characteristics; longer steps can be expected on a smooth, featureless surface than on a rough, irregular surface. Lighting conditions and TV sensor parameters also affect step length. In general, step length will vary directly with the picture quality, all other things being equal. The third factor affecting the step length is the degree to which vehicle behavior can be predicted. If vehicle behavior on a given surface cannot be predicted well, short steps must be used to prohibit failures.

The step length is perhaps the most important parameter affecting mission time. For each step that is made throughout the mission, a stop must be made, with all the resulting operations associated with each stop. Thus, if the average step length is doubled, the required number of steps and stops required to traverse a given distance is halved. This represents a decrease in mission time of approximately 25%. It is therefore highly desirable to increase step lengths to the greatest value possible consistent with safe vehicle operation.

A number of design features may be used to promote longer step lengths. First, step length is greatly influenced by vehicle mobility capability. Thus, the better the mobility of the vehicle, the longer step length that can be attempted on a given surface. By accurately calibrating the vehicle capability on given surfaces, the vehicle behavior can be predicted well, allowing greater confidence, and longer step lengths. A high-performance TV system will also serve to increase step length. Perhaps the most important means of achieving longer step lengths is through the use of closed-loop control and prediction aids. Of these two, closed-loop control is believed to be the more important. By informing the operator of the vehicle's behavior as a step is in progress, an opportunity for the operator to effect corrective actions as necessary to the vehicle is provided. This allows the operator to attempt longer step lengths, since he need not depend completely upon his own estimates and computer predictions as to vehicle performance.

2.2.4 Fixed Perception Cues

The possibility of fixed perception cues as aids to the operator in driving the vehicle has been suggested. Typical of such fixed perception cues would be viewing a part of the vehicle itself in the TV picture. The direct benefit of such a perception cue is the ease with which the overall geometry of the view can be constructed by the operator for the surface assessment procedure.

Fixed perception cues are believed to be unnecessary. To include a fixed perception cue in the viewed scene in general would require a large depression angle, or a physical extension of the vehicle into the viewed scene. Either alternative is not desirable. A large depression angle sacrifices a large portion of the field of view to accommodate a small portion of the vehicle in the picture. In general, this would ultimately result in the requirement for more pictures to achieve any given mission. These extra pictures would result from the necessity to raise the camera depression angle frequently to look ahead of the vehicle a sufficient distance to achieve strategy decisions. Another disadvantage is the apparent size distortion of the viewed portion of the vehicle. The other alternative of physically placing an object in the field of view is a rather inefficient means of accomplishing the end goal.

A fixed perception cue is of most benefit to an operator who is initially learning the entire problem of remotely controlling the vehicle. However, as he becomes more proficient in his task, reliance on the fixed perception cue is diminished. It would therefore appear to be desirable to train the operators to perform without the fixed perception cues. Initially, the performance of the operator will suffer. However, as his proficiency increases, the performance for the two modes of operation will be essentially identical. Therefore, a fixed perception cue is convenient at first but unnecessary for long-term performance.

This hypothesis was borne out in the ETM test program. For a short period, the vehicle was operated with a camera depressed sufficiently to view the front edge of the tracks in the picture. However, it was soon thought that this mode of operation with a large depression angle severely penalized performance. It was therefore decided to operate without fixed perception cues. As expected, this proved to be rather difficult at first. However, as the geometry of the situation became more familiar to the operator, little difficulty was experienced in evaluating the viewed scene.

It should be noted that the blind spot ahead of the vehicle directly affects the ease of assessing surface geometry. As the size of the blind spot is increased, it becomes more and more difficult to relate the vehicle to the viewed scene. Thus, the desire to maintain a small blind spot lies not in the concern that obstacles may be in the blind spot, but rather in the ease of relating vehicle-surface geometry. Therefore, as camera height is raised, it is desirable to place the camera farther back on the vehicle so that the size of the blind spot is kept as small as possible. This characteristic was also noted in determining the most suitable camera location on the vehicle for the ETM tests.

2.2.5 Safety Factor

Considerable effort was expended towards the determination of a safety factor to be used in controlling the vehicle. This safety factor would be the difference between the known capability and the capability which can be safely utilized due to inaccuracies and unknowns in the operator's information. First a rather complete calibration of the vehicle mobility capability was to be done. This calibration defines the vehicle capability as a function of various surface conditions. The second step was to determine how well the operator can assess the viewed scene as displayed on the television monitor. Specifically, the results of the development test surface assessment studies were to be used as measures of surface assessment performance. The errors introduced by the operator in assessing the surface as seen on the television monitor constitute uncertainties which must be considered in arriving at the vehicle's "effective mobility performance". A required control system performance was to be determined by mission analysis to determine the required probability of success for each control decision. From this analysis, the required safety factor for each decision could be determined. Thus, the vehicle mobility capability must be decremented by a factor relating the uncertainty in assessing a particular feature to arrive at the effective mobility capability. This decrement then is the safety factor, a difference between the actual capability and the useful capability.

The inaccuracies noted in the development test metric judgements and confirmed in the size and distance judgements performed on the test course indicated that no practical means could be devised for establishing a meaningful safety factor under the existing conditions. The difficulties can be summarized briefly. To satisfy mission objectives, the required control system probability of success must be quite high, perhaps 0.995. To achieve this performance during the entire mission, each control step must be made with an extremely high probability of success, perhaps 0.99995. To achieve this performance, it is necessary that each hazard or obstacle be offset by a safety margin of perhaps 4σ, where σ is the dispersion noted in the metric judgements associated with that obstacle. It is assumed that the error distributions of the size estimates in the development tests are normally distributed. However, if the actual dispersions determined by the development tests were used, in many cases meaningless results would be obtained because the size of the standard deviation in many cases is a large percentage of the fundamental distance itself. Thus, if the actual mobility capability is offset by the required safety factor, the resultant effective mobility is zero. This difficulty also exists in angular measurements.

As the ETM test progressed, other factors associated with surface assessment illustrated further the difficulty of establishing a safety factor in an extremely rough surface. The development test surface assessment studies indicated that the ability of an operator to assess accurately a viewed surface may be marginal. The large dispersions in estimating sizes, distances, and angles indicated that difficulty would be experienced in controlling the vehicle on the rough test course. These anticipated difficulties were indeed experienced. Two types of dangerous surface features have been defined: (1) an obstacle is a large, readily identifiable feature which, because of its size or orientation, must be avoided; (2) a hazard is a small-scale feature on the general surface or on a particular rock which may represent a mobility problem to the vehicle if encountered in a particular manner. In general, hazards are too small or inconspicuous to be readily detected. Either of these dangerous surface features can cause vehicle mobility failure and therefore constitute a control error. Any practical safety factor must incorporate both considerations. The difficulty of doing this is immediately apparent.

Usually, it was discovered that the vehicle experienced difficulty, not because of a single isolated features, but rather because of a combination of features, any one of which by itself would be no problem to the vehicle. Therefore, a worthwhile safety factor would have to account for these complex situations. On rough surfaces such as this, the vehicle's mobility capability is complicated by the manner in which the vehicle encounters any given surface feature. If the encounter is in a favorable fashion, the vehicle continues on; if not, a mobility failure occurs. However, if a consistent and rigid definition of safety factor is to be established, a precise definition of vehicle mobility capability must be established.

Surface irregularities also affect the degree to which the vehicle responds to a control command. A very rough surface introduces many perturbations into the vehicle's path, making accurate prediction of the path somewhat difficult. This variability in the vehicle's actual path further complicates the effective formulation of a safety factor.

The following conclusions can be drawn. A consistent and meaningful definition of a safety factor cannot be derived for the rough type of surface used in the ETM tests; i.e., near the vehicle's mobility limits. The many interrelations of features and slopes would require a safety factor to be an N-dimensional, extremely complex mathematical expression. Even if such an expression can be formulated, it is beyond the capability of the operator to utilize it efficiently. The problem is directly related to the surface complexity. If the surface were generally featureless, even though it might be quite irregular in contour, a meaningful safety factor could probably be established. In this case, the safety factor would be concerned primarily with isolated problems of bearing strength, slopes, and obstacle sizes. As the surface complexity increases, the surface assessment procedure becomes less exact, less of a science and more of an art. Hence, the applicability of a numerical safety factor decreases, since more and more interactions and uncertainties are present. As the surface complexity increases further, the safety factor eventually becomes meaningless as in the present case.

It should be noted that a definite distinction exists between surface complexity and the mobility capability in establishing a safety factor. A simple surface may exceed the mobility capability of the vehicle, even though a precise definition of safety factor can be established. In this case, the safety factor is of high value, since it can be used to best advantage in operating the vehicle through or around such areas. On the other hand a complex surface may not be near the vehicle's mobility capability. However, a precise definition of safety factor is not likely. The value of the safety factor and likewise of the remote control function is therefore diminished. In this eventuality, the remote control function can only serve to avoid obviously dangerous features.

The formulation of the safety factor in a test program was partially effective. Several definite trends were noted and should be observed in future control studies. Remembering that mobility hazards are unique to any given vehicle, those features of most concern to the operators in these tests were the following, in approximate order of priority.

1. Track wedge conditions
2. Rock undercut conditions
3. Narrow passages
4. Strut hangup
5. Excessive body angle conditions
6. Undercarriage clearances

The difficulties presented by these features can be expected to diminish as further mobility refinements continue. However, it may well be that two or three of the most troublesome features could be singled out, and associated safety factors assigned and used. In conjunction with this limited or partial safety factor, a more precise definition of vehicle mobility would be highly desirable. The operator would also benefit from extensive training and operator aids. Neither of these were available in the test program due to time and program scope limitiations.

2.3 VEHICLE AND CONTROL SYSTEM

The SLRV Phase I ETM vehicle and control console were modified to increase mobility and to meet the operational requirements of this study.

The driver's control system consists of three consoles: (1) driver ancillary console (modified Phase I console), (2) driver display console, and (3) stereo display.

2.3.1 Vehicle Modification

As a result of preliminary tests on the outdoor foundry slag test course, various design changes were incorporated. These modifications provide increased mobility on the random course. Other changes were made to provide additional instrumentation, principally the stereo TV system. The Phase I vehicle configuration and the modified configuration are shown in Figure 2-8. The modified vehicle is shown in Figure 2-9.

With the additional instrumentation the vehicle weight increased to 137 lb. This raised the center of gravity and created a less stable vehicle. To obtain the Phase I stability characteristics, vehicle track base and span were increased.

Design changes for the traction drive assemblies were incorporated to reduce the type of hangup problems encountered during Phase I. The Phase I failures due to wire hangup or foreign objects in the traction drive assembly were eliminated.

2.3.1.1 Traction Drive Assembly

The traction drive assembly configuration was changed to improve performance on a random test course. Rims were changed from shaped (convex) stainless steel of 0.008-inch thickness to flat 0.012-inch thick stainless steel. Width of the track was changed from 3.0 to 3.5 inches. Tread material for Phase I was foam silicon rubber. Materials with better abrasion resistance were investigated and polyurethane was selected. The use of polyurethane has demonstrated a greatly increased durability over that of the Phase I foam silicon rubber.

A second idler wheel directly below the traction drive pivot was incorporated to provide a triangular type of configuration of the traction

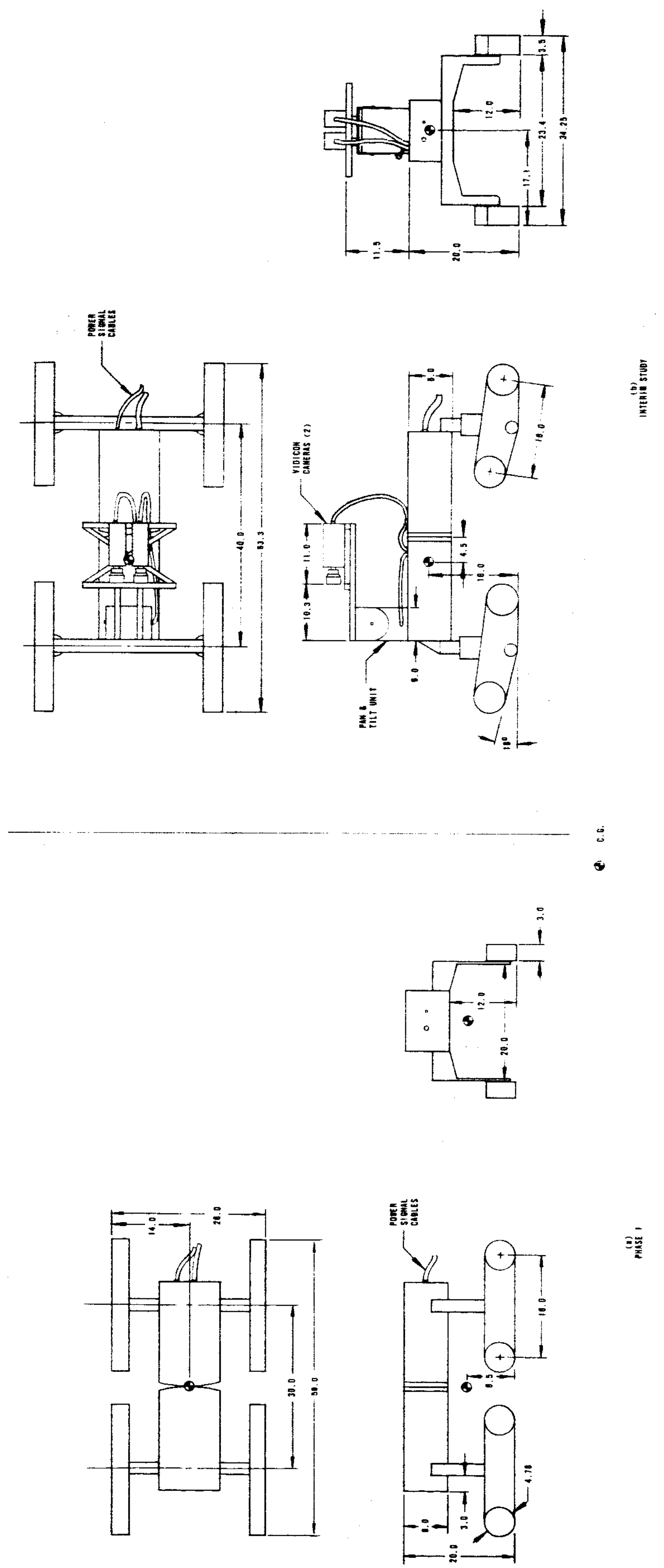


Figure 2-8 Vehicle Configuration

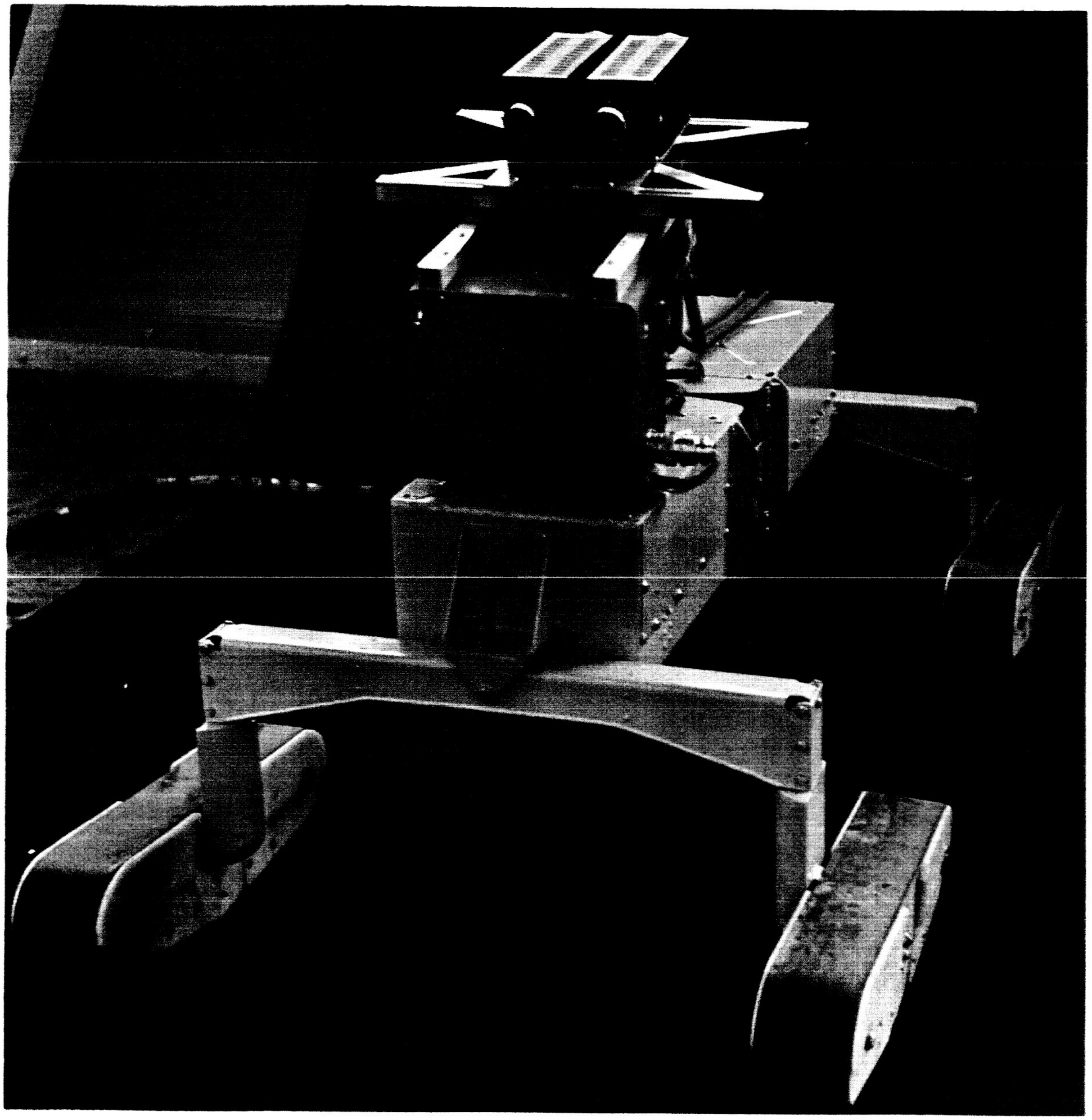


Figure 2-9 Modified ETM Vehicle

drive assemblies. This track presents a toe-up type of approach to obstacles. Nylon cover plates were installed on both sides of the traction drive assemblies, and the Phase I nylon guides on the idler wheel were removed. The new covers furnish a guide for almost 50% of the rim and eliminated Phase I problems of foreign material entering the traction drive assemblies since they completely enclose the assembly. Figure 2-10 shows the modified track configuration with and without the nylon cover plates installed.

2.3.1.2 Strut, Gross Beam, and Front Pivot

New struts and cross beams were fabricated using the box or tubular principle. Track base and spacing were increased to maintain stability characteristics similar to the Phase I vehicle. All wires leading to the traction drive assemblies run inside the box structure cross beam and strut through a tube into the traction drive assembly. Figure 2-11 shows the vehicle without tracks; the new cross beams, struts, pivot, and the wire entry for traction drive assemblies can be seen.

A front beam pivot was utilized to provide pivoting in the roll axis for the front support beam. Angular displacement is 15° on either side of the normal horizontal axis of the beam.

Traction drive limit stops have been retained at $\pm 45^{\circ}$, the same as used for the Phase I ETM; Section 2.5 gives test information for retaining these limit positions.

2.3.1.3 Electronics

Various relays and diodes were added to the vehicle to obtain added flexibility in the automatic command mode. A synchro transmitter was added to the forward body section for transmitting bearing to destination (manually set by cable handler) information to the driver display console.

Wiring was altered for these modifications and the steering lock indicator circuitry was changed. The steering lock displays (located on the driver ancillary console) are energized by utilizing the steering position switches as in Phase I, but the steering actuator does not need to be in a locked position as in Phase I to obtain a steering lock position indication.

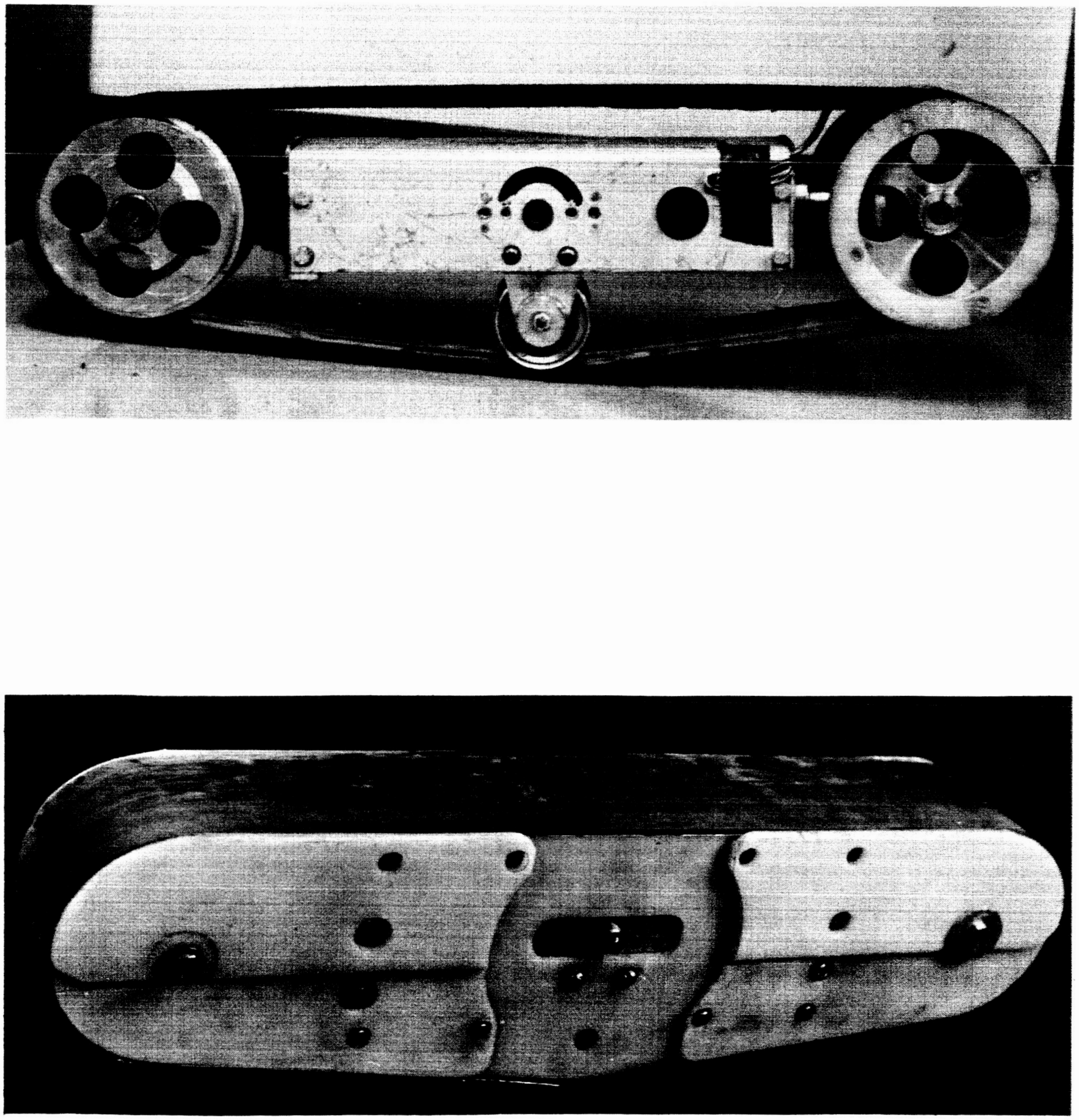


Figure 2-10 Modified Track Configuration

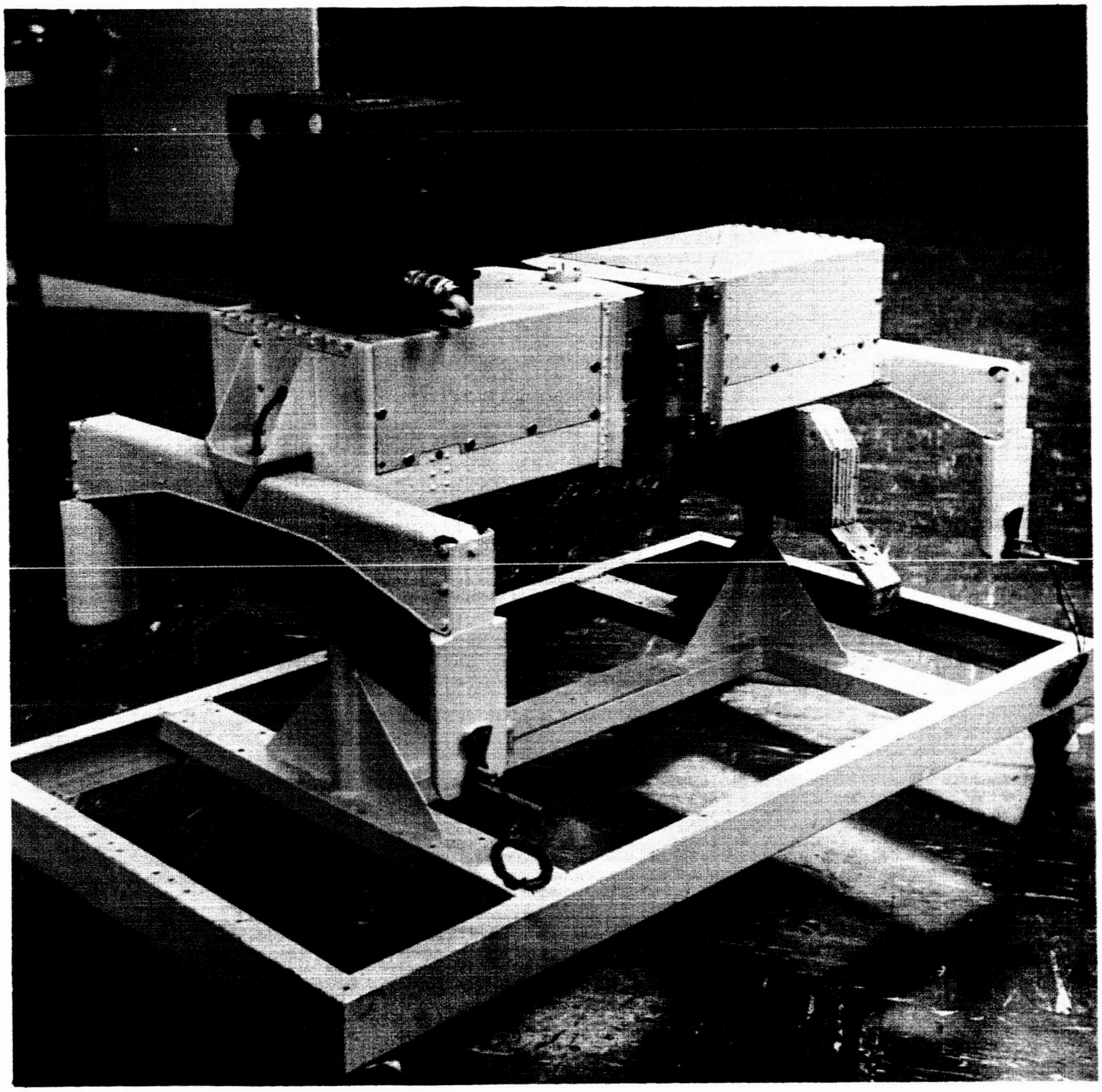


Figure 2-11 Modified Vehicle Without Tracks

2.3.1.4 Cables

Cables 150 ft long have been fabricated with switches located 10 ft from the vehicle for emergency stopping without a time delay. All wires between control consoles and vehicle are contained in one sheath.

2.3.2 Driver Ancillary Console

Modifications to the driver ancillary control console provide increased flexibility in the automatic command mode and virtually eliminate the need for operation of the vehicle in the manual mode. However, the manual command capability is retained. The automatic control assembly was relocated to facilitate operator contact. A new connector was added to the side of the cabinet for connection to the driver display console. Figure 2-12 shows the driver control console.

2.3.2.1 Manual Operational Modes

All manual modes of operation exist as in Phase I. Selection of three speeds or zero speed, in either a forward or reverse direction, is provided for each track. A manual drive button for commanding motion of all tracks simultaneously is still provided.

2.3.2.2 Automatic Operational Modes

Various modes of operation were added to the automatic control mode. The available modes are listed in Table 2-4.

Individual lights indicate the forward or reverse speed selected, independent of turn conditions.

2.3.2.3 Steering Unlock Switch

The steering unlock switch wiring was changed to provide operation of the vehicle without a steering lock during all phases of control. To eliminate the steering lock during any mode of operation, the switch must be depressed continuously.

2.3.2.4 Attitude Limit Meter

The limit meter was removed and placed on the driver display console with a similar meter to present both pitch and roll angles

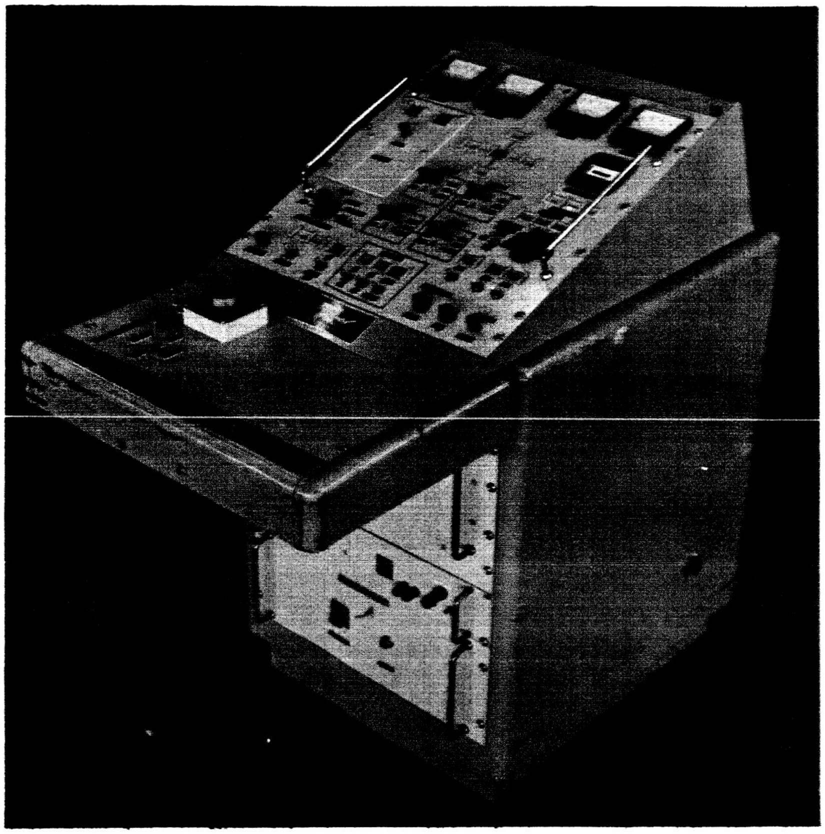


Figure 2-12 Driver Control Console

TABLE 2-4

AUTOMATIC CONTROL MODES

Auto Mode Switch Position	Type of Command	
$N_1 - N_2$	N_1	Forward or reverse
	N_1 and N_2	Turns*
$N_1 - N_3$	N_1	Forward or reverse
	N_1 and N_3	Turns*
$N_1 - N_0$	N_1	Forward or reverse
	$N_1 - N_0$	Transient turn
	$N_1 - N_2$	Steady-state turn
$N_2 - N_3$	N_2	Forward or reverse
	N_2 and N_3	Turns
$N_2 - N_0$	N_2	Forward or reverse
	N_2 and N_0	Transient turn
	N_2 and N_3	Steady-state turn
$N_3 - N_3$	N_3	Forward or reverse
	N_3 and N_3	Turns (no turn available)
$N_3 - N_0$	N_3	Forward or reverse
	N_3 and N_0	Transient turn
	N_3 and N_3	Steady-state turn
Scuff Turn Switch Position**		
Right	Vehicle turns to right (2 right tracks reverse and 2 left tracks forward, speed selected by auto mode switch)	
Left	Vehicle turns to left (2 left tracks in reverse and 2 right tracks in forward, speed selected by auto mode switch)	

* Transient and steady-state.

** Motion is commanded by moving auto control stick to forward position simultaneously. The limit displays and reset control are retained on the driver console.

2.3.2.5 Power Limits

The power limit reset switch was changed to an on-off toggle switch with the off position serving as a reset when power limits are desired.

2.3.2.6 Delay Circuits

Existing delay circuits for reverse commands are utilized with the addition of delay circuits for forward and stop commands. These delays simulate signal transit and processing times for all stop and go commands. To simplify equipment, delays in turn commands are not incorporated. Three-second delays are used for the time delays.

2.3.2.7 Driver Control Desk Panel

Since the vehicle operator must view a TV monitor while driving the vehicle, it was necessary to relocate the automatic control assembly. Locating the driver ancillary console on the operator's right side appears advantageous.

2.3.3 Driver Display Console

The driver display console consists of three panels mounted on a single relay rack. The panels are (1) vehicle inclination, (2) camera angle and destination bearing panel, and (3) pan and tilt control panel. Figure 2-13 shows the front panel of the driver display console.

2.3.3.1 Vehicle Inclination Panel

The roll or pitch limit meter was removed from the driver console and a duplicate limit meter was installed on the vehicle inclination panel. Both roll and pitch inclination angles are now displayed with the capability of adjusting the plus and minus limits desired for each axis. When the vehicle reaches the preset limits in either roll or pitch attitude, power is instantaneously removed from the vehicle and motion stops. A reset switch for both pitch and roll which returns power to the vehicle is located on the driver console.

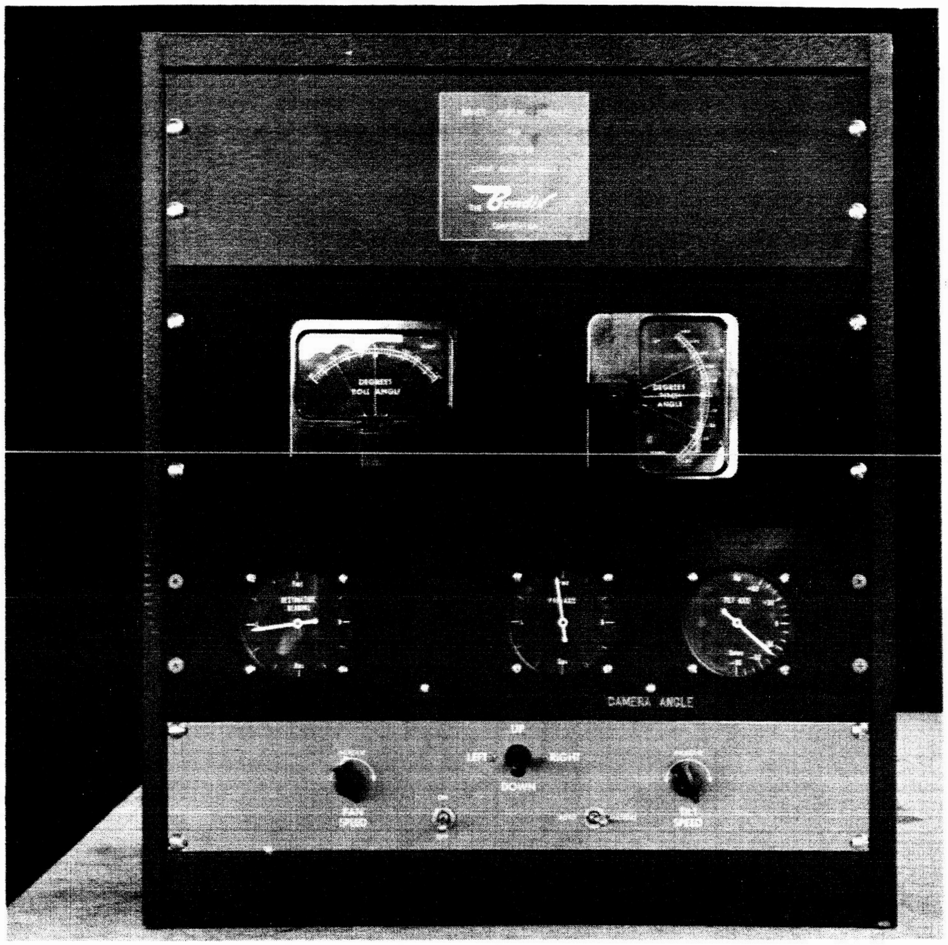


Figure 2-13 Front Panel of Driver Display Console

2.3.3.2 Camera Angle and Destination Bearing Panel

The camera angle and destination bearing panel contains three synchro display units. Two displays represent pan and tilt angles of the TV vidicon assemblies with respect to the vehicle (front section) heading and pitch, respectively.

A destination bearing display is used to indicate bearing to a preselected destination during a test run. This display is a synchro repeater with its associated transmitter located on the front half of the vehicle. During stopping periods, the dial on the transmitter is pointed toward the destination by personnel on the test course.

2.3.3.3 Pan and Tilt Control Panel

The pan and tilt control unit is a Pelco remote control model PT-1500PV, which contains controls for selecting variable pan and tilt speeds independently. A two-axis control stick is also furnished for controlling both axes independently or simultaneously. Variable speeds available are:

Pan - to 9.0°/second (no load)

Tilt - 4.5°/second (no load)

Rotational travel in pan is limited to 360° measured from any point desired. Tilt is capable of plus 60° to minus 90°.

2.3.4 Stereo Television Display

The stereo television system consists of a modified Sylvania color receiver and dual Sylvania vidicon camera units. The cameras operate on a common synch; however, they have separate video amplifiers. In operation, one camera drives the receiver red gun directly and the second camera drives a combination of the blue and green guns. Thus, a color anaglyph image is displayed on the TV monitor. When the image is viewed through the proper arrangement of red and blue/green filters, a monochrome stereo model is viewed.

The stereo TV equipment is shown in Figure 2-14 and consists of remote vidicon assemblies mounted directly on the vehicle, the remote camera control unit, and the modified color receiver.

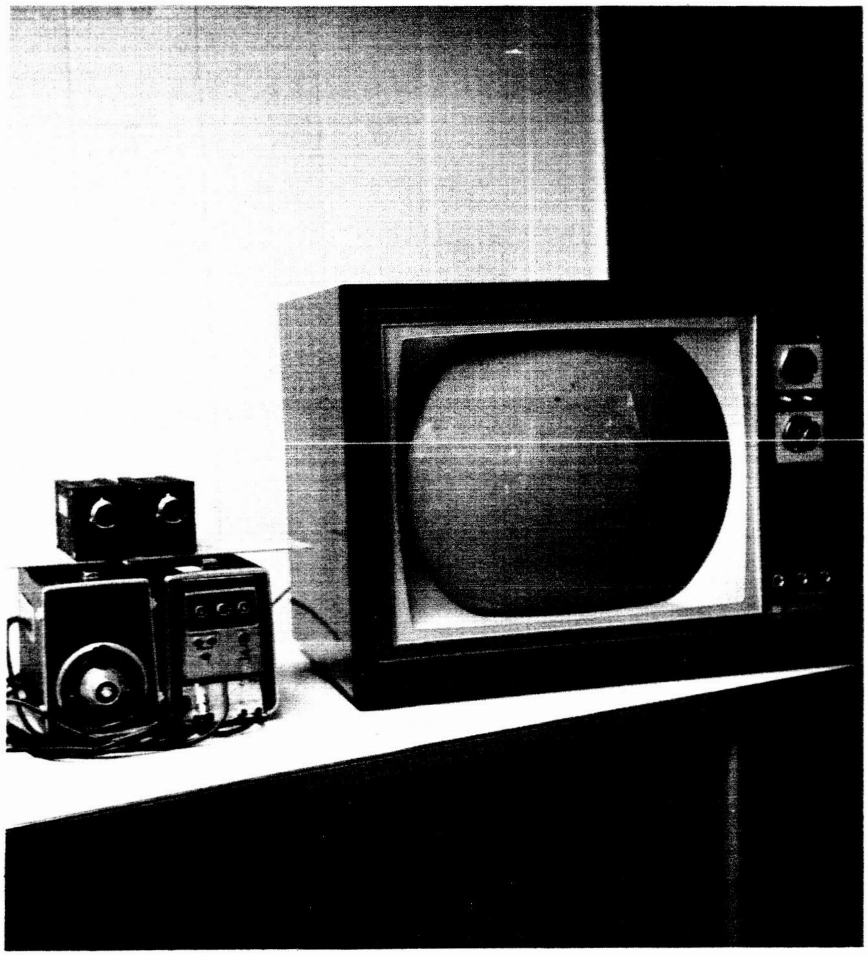


Figure 2-14 Stereo Television Equipment

2.4 TEST COURSE DESCRIPTION

The test program was conducted on an indoor course located at Willow Run Airport, approximately 10 miles from Ann Arbor, Michigan. The facility consists of 75 x 130 ft bay of an aircraft maintenance hangar leased from the Airlines National Terminal Service Company. A test course approximately 60 x 60 ft was used for the vehicle tests. The test course is shown in Figure 2-15.

2.4.1 Lunar Terrain Model

The test course surface consists of approximately 460 tons of foundry slag. Three hundred tons (approximately 200 cubic yards) of coarse grade slag was placed over 160 tons (80 cubic yards) of grade 22X slag having a grain size varying from that of sand to a particle size of 0.75 inch diameter to furnish the lunar terrain model. This presented a completely random terrain with some areas of the test course smooth with respect to the vehicle mobility system while other areas had surface hazards well beyond the vehicle's mobility capability. An eight-foot felt curtain surrounded the test course and an 8 x 12 ft control cubicle was located adjacent to the test course.

2.4.2 Lighting Details

Several alternate methods of providing test course lighting were studied. Two discrete problems were involved:

1. To provide collimated light over a large area at reasonable cost. The intensity of the lighting must be sufficient to allow use of a vidicon TV sensor.

2. To provide collimated lighting at various incident angles with respect to the test course terrain.

A solution of these two problems was the fabricating of two separate lightstands.

One lightstand (see Figure 2-16) was fabricated for use with low incident angles (20° to 40° with respect to the slag surface). Twelve theatre-type spotlights were mounted on the test fixture in three horizontal rows of four lights each. The top row was approximately 16 ft above the

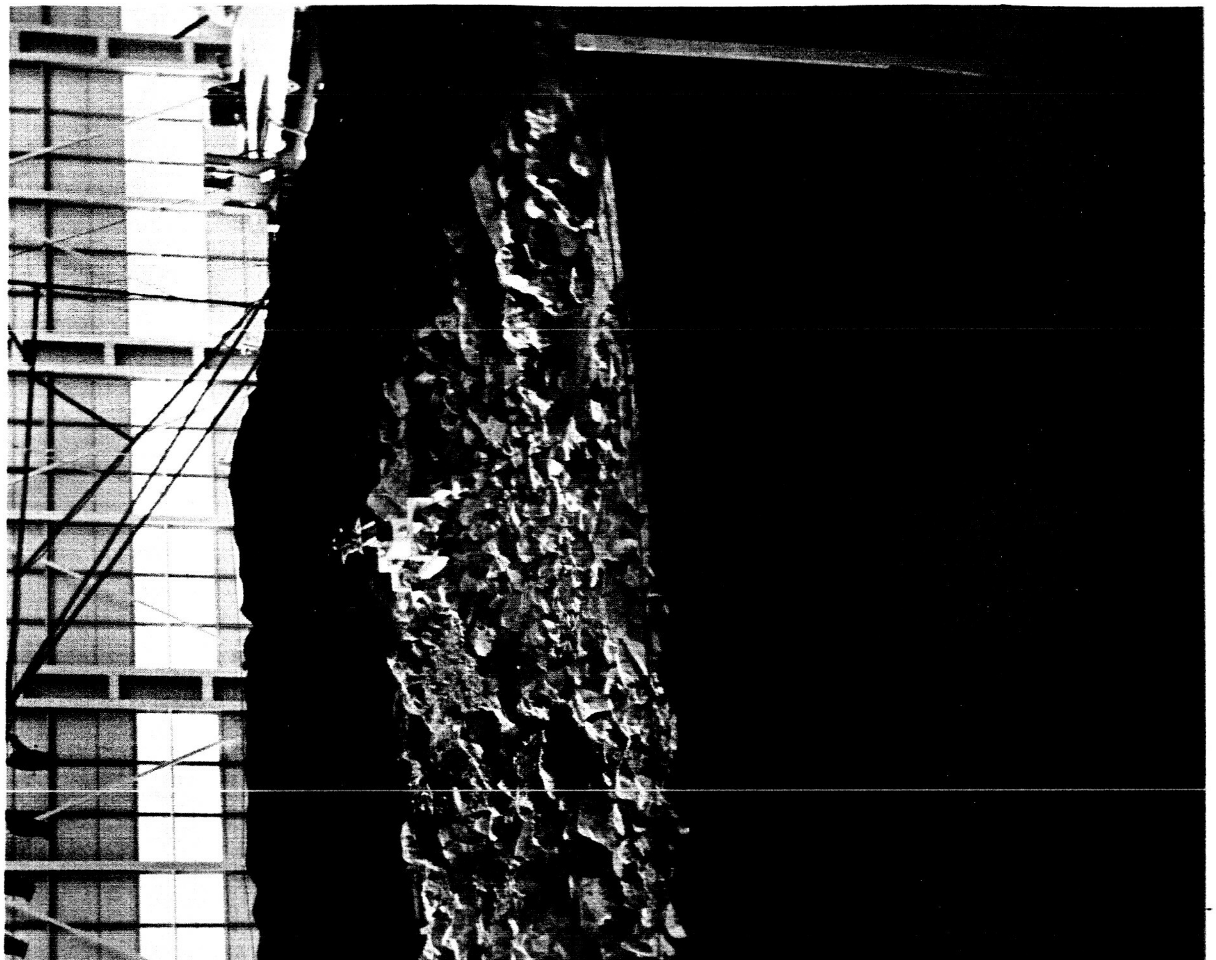


Figure 2-15 Test Course at Willow Run Airport

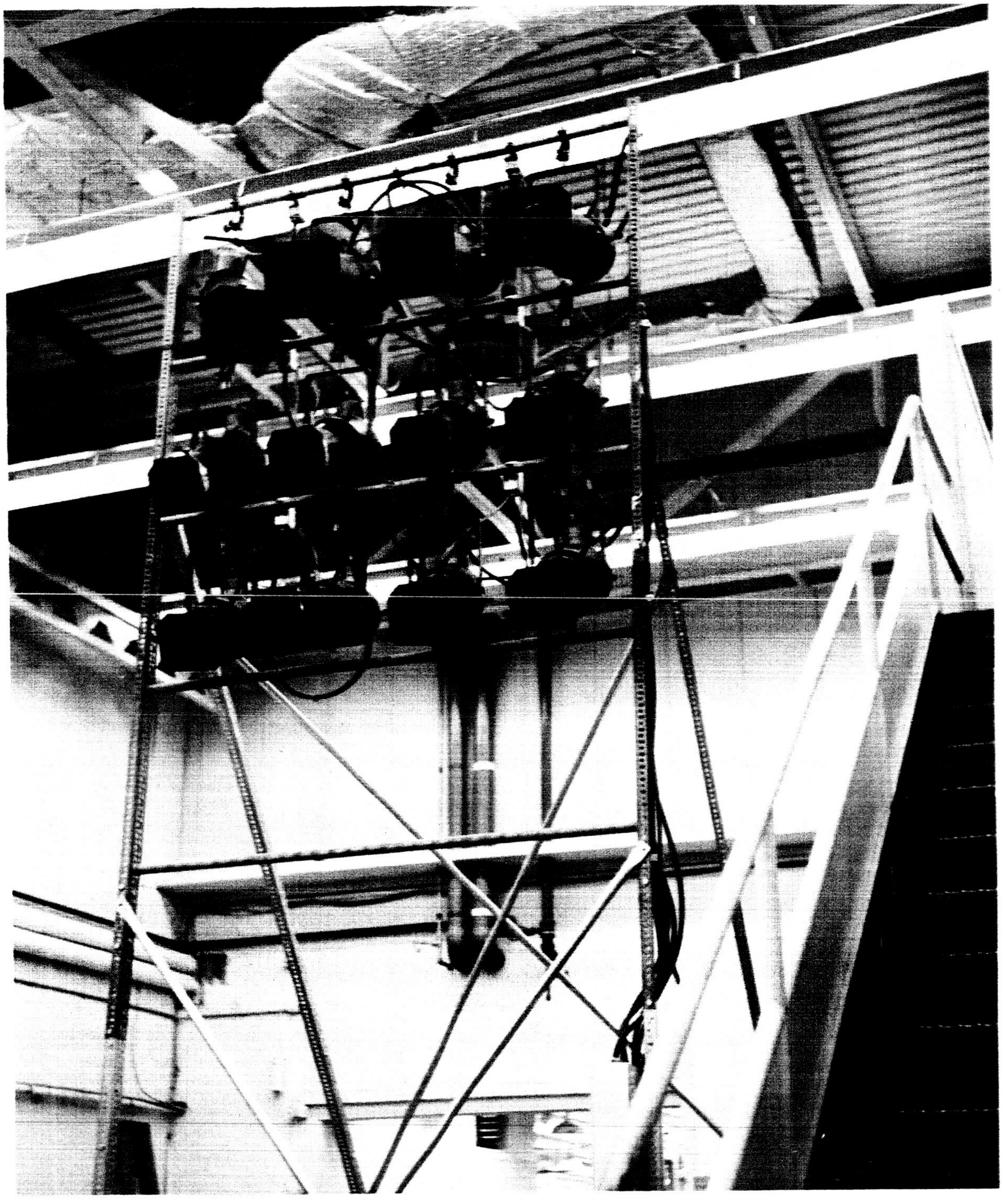


Figure 2-16 Light Stand for Low Incident Angles

model surface. The fixture was mounted on wheels for easy transport around the test course periphery to represent front, side, or back lighting with respect to the vehicle axis.

An additional lightstand was fabricated using a Bendix-owned fork-lift truck. A boom-type structure was attached to the front of the truck so that four theatre-type spotlights could be positioned approximately 20 ft above the test course at a distance up to 25 ft in front of the truck. This arrangement represented high sun angles with respect to the terrain model. This fixture is shown in Figure 2-17.

2.5 VEHICLE CALIBRATION

Before the remote control tests, the vehicle was calibrated to determine its mobility performance capability. These tests were performed to obtain a foundation for judging vehicle reaction to given commands over various discrete objects. Although reaction to individual discrete obstacles cannot be applied directly to the type of reaction obtained on a random surface, it does give a basis on which to make initial judgements. After vast experience has been gained on a random surface by an operator, the experience gained on discrete obstacles will not be necessary. Tests were conducted with the operator within viewing distance of the vehicle. The TV system was mounted on the vehicle to standardize the weight and balance; however, it was not energized during the tests. Tests were conducted on two types of surface: a controlled (flat plywood or cement) and a random surface (slag). Coefficient of friction between vehicle tracks and plywood is 0.7.

2.5.1 Controlled Surface

The following tests were conducted with the results obtained as listed:

1. Plywood 45° undercut crossing capability

   a. Climbed 15.24 cm

   b. Failed 16.51 cm

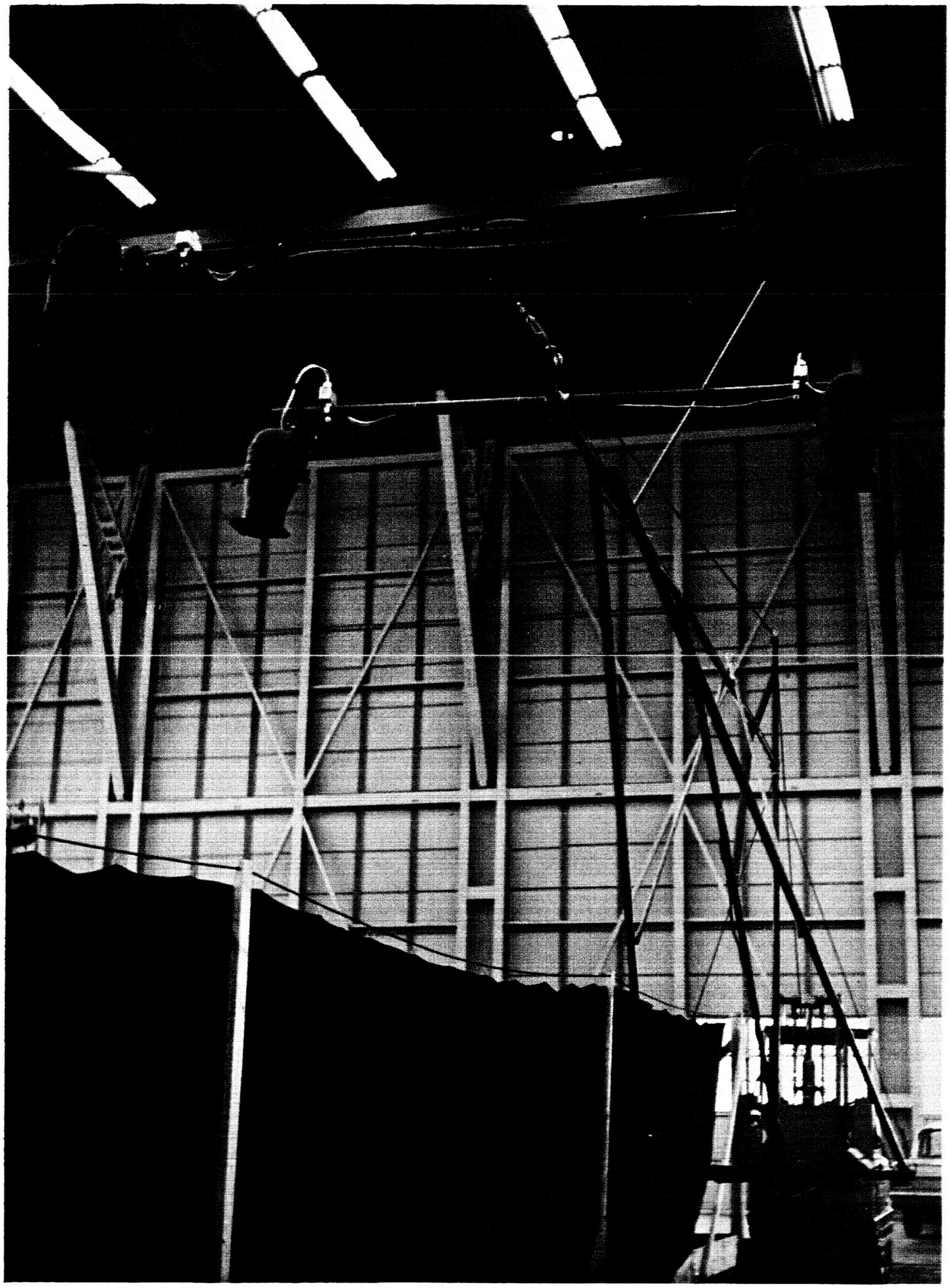


Figure 2-17 Light Stand for High Sun Angles

2. Two-track 90^{o} step capability (plywood)

   a. Climbed 44.1 cm

   b. Failed 45 cm

   c. Figure 2-18 shows this test setup. Results listed herein apply to both the pivoting and locked front cross beam vehicle configuration

3. Single-track 90^{o} step capabilities (plywood)

   a. Pivoting cross beam (front)

      Climbed 38.1 cm
      Failed 41.9 cm

   b. Locked cross beam (front)

      Climbed 33 cm
      Failed 35.6 cm

4. Slopes (plywood)

   a. Maximum forward or reverse slope that the vehicle could negotiate was 35.5^{o}

   b. Maximum side slope on which the vehicle could move with negligible side slip was 35^{o}

5. Crevice crossing capability (pivoting cross beam, plywood)

   All distances in centimeters

Angle approach to crevice	Fwd.	Rev.	Crossed	Failed
30^{o}	x		21	23
		x	20	22
45^{o}	x		28	29
		x	26	28
60^{o}	x		30	32
		x	29	31
90^{o}	x		36	40
		x	35	38

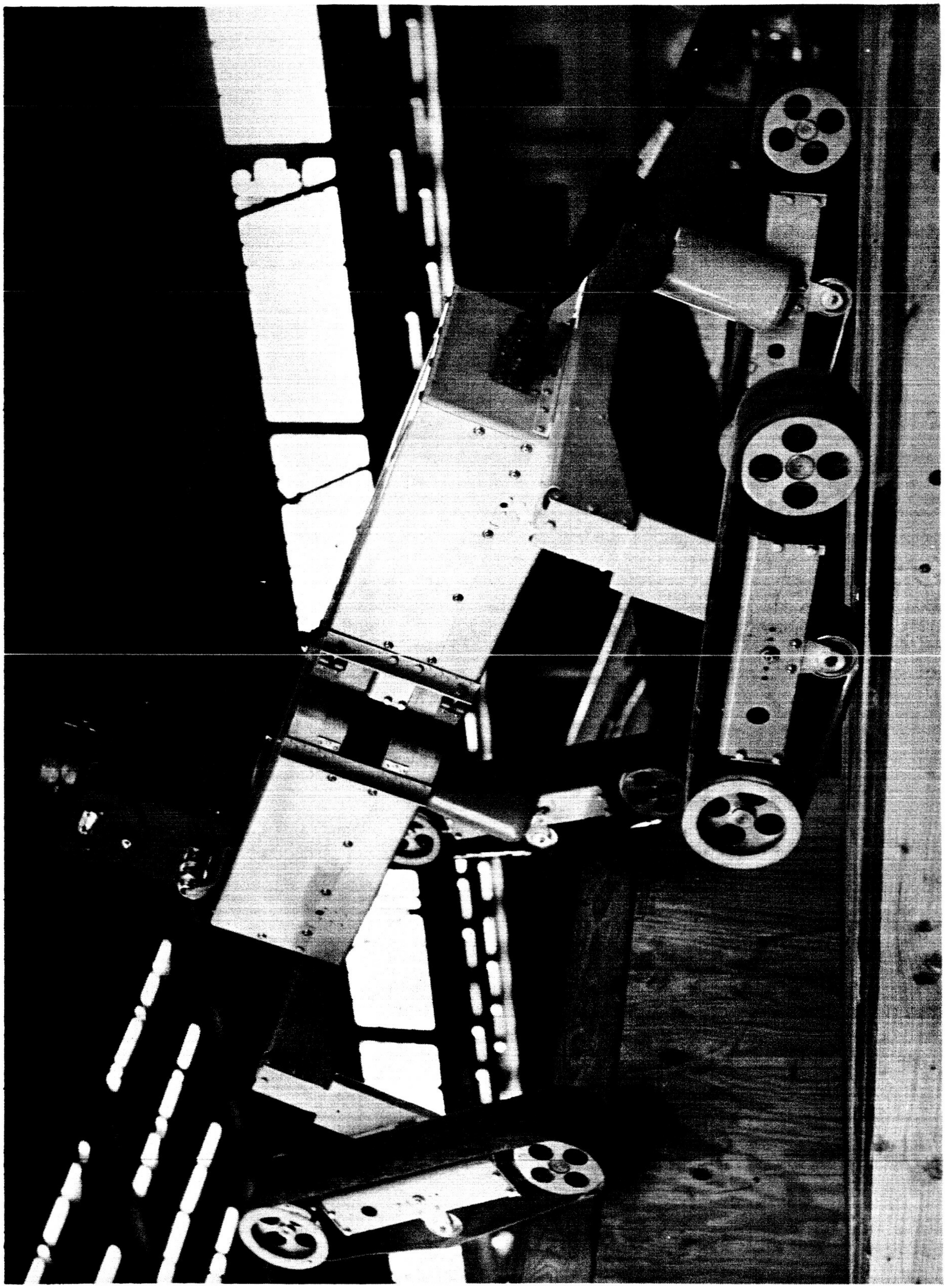


Figure 2-18 Vehicle Test Setup

6. Turning Diameters

   a. N_1/N_2 automatic mode - 5.03 meters

   b. N_1/N_3 automatic mode - 4.57 meters

   c. N_2/N_3 automatic mode - 5.18 meters

7. Static stability

   a. Roll - $\pm 42^{\circ}$

   b. Pitch - $\pm 80^{\circ}$

2.5.2 Random Surface

Calibration tests conducted on the random (slag) terrain provided quantitative rather than qualitative data. Throughout this phase of testing the task of operator training and familiarization was conducted. Operator proficiency in determining vehicle performance capabilities and limitations with respect to the surrounding terrain was improved.

All automatic modes of control were utilized during these tests to establish the preferred mode. After various tests, two modes of operation were selected: (1) N_1/N_3 - automatic mode, and (2) manual crimp modes used to obtain maximum body bending in minimum space. Automatic mode N_1/N_3 gave the shortest turning diameter and also appeared to be more predictable in reaction to commands over random terrain.

During this portion of the test program it became evident that the $\pm 45^{\circ}$ limit stops for traction drive assemblies were preferred over the larger limits. With the larger limit stops incorporated in the vehicle numerous failures occurred due to the traction drive assembly tipping (toe down) down too far. This caused the vehicle to drive into crevice-like terrain instead of crossing safely.

The following group is a list of various items affecting the vehicle maneuverability. It should be explained at this point that the results obtained are somewhat subjective in nature.

2.5.2.1 Terrain Grain Size

Individual grain size of a terrain has little effect on a command signal decision if all grain sizes are less than 2.5 to 5 cm in diameter and steep slopes are not present. If the grain size is completely random or consists of all sizes larger than 5 cm in diameter, various results are observed. The path desired must be selected and then analyzed for variations of the surface. It was observed that individual grain size had little effect on the decision, but rather the variation of the basic contour was the factor in each decision. One important fact demonstrated was that as the surface became more irregular, it became more difficult to predict turning diameters and rates. Thus, on a random terrain with large (over 20 to 25 cm) grain size only short distance (1/3 to 1 meter) could be predicted with any amount of accuracy.

2.5.2.2 Side Slope

Effects of side slope or side slip on a random terrain are difficult to evaluate. No precise tests of this nature were conducted, but it was noticed during many test runs that side slip did occur on single discrete obstacles.

The type of obstacle contributing to this condition was surfaces not affording sufficient width for full track width support normal to the track surface. Problems encountered with this type of obstacle could and in many cases did lead to a track wedge condition or strut hangup.

2.5.2.3 Vehicle Attitude

Vehicle attitudes have little or no effect on its maneuverability. The only caution that must be exercised during a command decision execution is that the dynamic attitude limits are not exceeded.

2.5.2.4 Single Obstacles Near Mobility Limits

Caution must be exercised when approaching or negotiating obstacles near the mobility limits. Generally a heading change induced by the single obstacle could be expected. As an example, a large rock in front of the right front track will probably cause a heading shift to the vehicle's right.

2.6 VEHICLE CONFIGURATION

The configuration tests established the group of vehicle parameters listed prior to performance of the evaluation testing. Tests were conducted by trained operators remotely controlling the vehicle over the random test course through use of stereo TV.

2.6.1 Step Distance Control

Until the first group of tests was conducted it was considered adequate to control step distance by use of a timer controlling vehicle motion time. It became apparent immediately that this type of distance control was inadequate. When time-controlled motion was utilized, the desired step length was never obtained. To approximate the presence of an odometer, the individual step length desired was controlled by test course personnel, thereby increasing operator control over vehicle path.

2.6.2 TV Field of View

Three TV fields of view were investigated:

1. 33° horizontal by 24° vertical
2. 52° horizontal by 38° vertical
3. 70° horizontal by 50° vertical

Using a variety of locations, the field of view was changed for each scene as monitored on the stereo television. In each case as the horizontal field of view decreased a larger number of pictures was required to select an acceptable path. For these test conditions it was considered best to use the widest field of view: more information is presented at one time and less memory capability is required.

2.6.3 TV Position

The configuration of the vehicle allowed for four possible TV locations: (1) lower front (directly on top of the pan and tilt unit), (2) upper front (variable between 6 and 12 inches above the pan and tilt unit), (3) lower rear (10 inches to the rear of item 1) and (4) upper rear (same as item 3 except variable between 6 and 12 inches higher).

A series of tests runs were conducted to evaluate all four TV positions. Although the resultant position selected was subjective in nature, the following reasons were used by the operators in determining the final operating position.

1. Lower front position: When sufficient coverage was obtained directly in front of the vehicle, the vertical field of view was not adequate for making long step decisions. The forward location presented too large a blind spot when a smaller depression angle was used.

2. Upper front position: The same problems encountered with the lower front position were also experienced with this position. Also, the higher camera position presented greater difficulty in assessing the surface directly in front of the vehicle.

3. Lower rear position: This position appeared to be the most satisfactory of all positions. One standard camera angle could be used, with adequate picture depth and very small blind spot. Fewer pictures were required to obtain sufficient information for making proper control decisions.

4. Upper rear position: This position presented the same type of problems as the upper front position; namely, the lack of field of view in front of the vehicle when observing areas close to the vehicle.

2.6.4 Stereo Baseline

The stereo baseline used during all remaining tests was 4 inches. The operator was able to fuse the large disparity images resulting from viewing a close object with a 10-inch baseline condition. However, a 4-inch baseline picture was judged to be easier to view by the operator. The 4-inch baseline picture presented good picture definition and depth cues.

SECTION 3

DEVELOPMENTAL TESTS

The purpose of the developmental test program was to determine the influence of various viewing parameters on surface assessment. These tests did not require the use of the ETM vehicle or the test course; several separate experiments were devised to study the differential effect of various system design parameters on related operator tasks. These experiments are discussed in detail in this section and include:

1. Surface assessment experiment
2. Transmission degradation
3. Surface lighting
4. Path prediction.

3.1 SURFACE ASSESSMENT EXPERIMENT

3.1.1 Summary

An experiment was conducted to determine the accuracy with which subjects could make quantitative judgements of the geometry of a generally rough and unfamiliar scene by viewing optical images of the scene. Twelve subjects each made 82 judgements of distance between marked data points, the inclination (off horizontal) of a line connecting those data points, and the horizontal distance from the camera station to a point midway between the marked points. Each of the 82 trials used a different pair of data points distributed among 5 different scenes and distributed according to range, orientation, and size in accordance with ranges of values of concern to remote control of a 150 lb SLRV. Results show an overall group standard deviation of error of 10.9 inches on distance-between judgements, 20.8^{o} on inclination judgements, and 23.6 inches on distance-to-midpoint judgements. Mean errors for the group as a whole were generally small. The rate of learning was generally low even though subjects were given the correct value after each judgement. Performance by the groups using stereo images was only slightly better than the group using monocular images. An accurately scaled grid representing a horizontal plane proved to be of little aid in making accurate judgements. Controlled stimulus conditions of data point pair range and orientation had a greater influence on performance than any of the controlled imaging system design factors.

3.1.2 Introduction and General Approach

A significant part of the remote control problem is associated with assessing the geometry of the unfamiliar lunar surface to determine if it is safe to move in the desired direction and if not to select an alternate route. The accuracy with which this task can be performed is one measure of remote control performance. The related design task is to provide a system of sensors and information processing to maximize the accuracy of surface assessment. A portion of this control study was devoted to the discovery and investigation of factors which influence the accuracy of surface assessment by means of observer judgements made from optical images of the surface under consideration.

Surface assessment judgements could be made subjectively by an observer viewing an image of the surface having acquired knowledge of the vehicle's mobility capability by training and experience. Alternatively, surface assessment could be accomplished more quantitatively by numerical comparison of critical surface dimensions with the vehicle's measured mobility capability. An essential element in either procedure is the ability to interpret the surface geometry correctly. The main difference between the two procedures is that in one case judgements are qualitative and related to the capability of a specific vehicle. Accuracy of these judgements would be difficult and time consuming to evaluate in a brief test program, particularly where the vehicle's capabilities have not yet been established for a random surface. In the other case, judgements are independent of any particular vehicle configuration and the accuracy of judgements can be easily and precisely established.

An experiment was designed and executed in the first half of this study program to explore the accuracy of surface assessment as a function of various controlled parameters using quantitative judgements of surface geometry as the subject's task. Judgements of "distance between", "inclination", and "distance to" specified data points on a simulated random lunar terrain (created by foundry slag) were made. The ranges of actual values selected for the controlled data points were intended to cover the range of values of interest for a 150-lb vehicle design. The general procedure selected for use in the experiment was to have subjects view stereograms, produced by photographing TV images of the simulated lunar surface, through a simple stereoscope. This procedure and apparatus permitted exploring the effects of stereo vs monocular imaging systems without the subject necessarily being aware of which condition he was viewing. Performance with a monocular system was simulated simply by making both images in the stereogram identical.

The requirement to explore performance as a function of various stereo baseline conditions required the use of a systematic procedure for selecting subjects who were capable of stereoscopic perception. This selection was based upon a stereo perception screening test given to potential subjects. Also, to hold the experiment within manageable proportions, it was necessary to hold the number of controlled conditions to a manageable number. To select certain conditions and also to verify and check out the various details of the experimental procedure, two pilot experiments were conducted; one primarily concerning the selection of stereo baseline conditions, and the other primarily concerned with the use and construction of scaling grid overlays. The following sections describe and discuss the screening test, and pilot test, and the main experiment in detail.

3.1.3 Stereo Perception Screening Tests

The stereo perception screening tests ensured that all subjects were capable of stereo vision and familiarized them with use of the viewing apparatus, a Keystone View Company stereoscope.

A total of 24 persons available to the study program as possible test subjects were screened for stereo perception. Of these 24, only 7 were found to have "good" stereoscopic ability, 9 were judged "fair", and 8 had "poor" stereoscopic capability. Twelve subjects were required for the main experiment and it was originally intended to select these 12 from the screening test. However, since the screening test did not yield 12 persons with "good" stereo perception, it was decided to use both those with "good" and "fair" ability in the subsequent pilot studies. This yielded 15 subjects. (One of the "good" subjects was to assist in the setup of the experiment and became ineligible to serve as a subject.) The necessary 12 subjects for the main experiment were later selected on the basis of performance in the pilot tests as described later.

The stereoscopic capability of each subject was determined on the basis of his ability to perceive spatial relations correctly in abstract stereograms devoid of monocular cues. Stereograms used in this screening test were selected from "Dr. Wells' Selection of Stereoscopic Charts" published by American Optical Co. A total of 13 stereograms were selected (1) to familiarize subjects with the viewing apparatus and establish the best viewing conditions for the subject, (2) to establish stereoscopic ability, and (3) to establish ability to fuse images of various spacings. Four of these 13 stereograms provided the basis for ranking stereoscopic ability. Three of these are shown in Figure 3-1.

3.1.4 Pilot Experiments

The purpose of the pilot experiments was to test equipment operation, develop operational procedures, and select stereo baseline and synthetic grid conditions for use in the main developmental test experiment.

The pilot experiments used photographs taken from a TV monitor displaying an image of the simulated lunar surface. The simulated lunar surface was constructed of foundry slag with particle sizes ranging from sand to three feet. A sample of the area is shown in Figure 3-2. The area was approximately 30 ft square. Contract prints 2-1/4 inches square of the views were mounted as stereograms for viewing in the Keystone stereoscope. A typical stereogram is shown in Figure 3-3. Perspective grid images were produced in a similar manner from TV images of a grid laid out in white tape on a black floor and photographed with the same camera viewing geometry as was used for viewing the simulated linear scenes. A typical stereo grid is shown in Figure 3-4.

The equipment used in the pilot experiment and in the main experiment consisted of:

1. Kintel closed-circuit TV system

2. Special fixture to permit precise adjustment of camera baseline and convergence angle

3. Still camera (Yashica "D" twin lens).

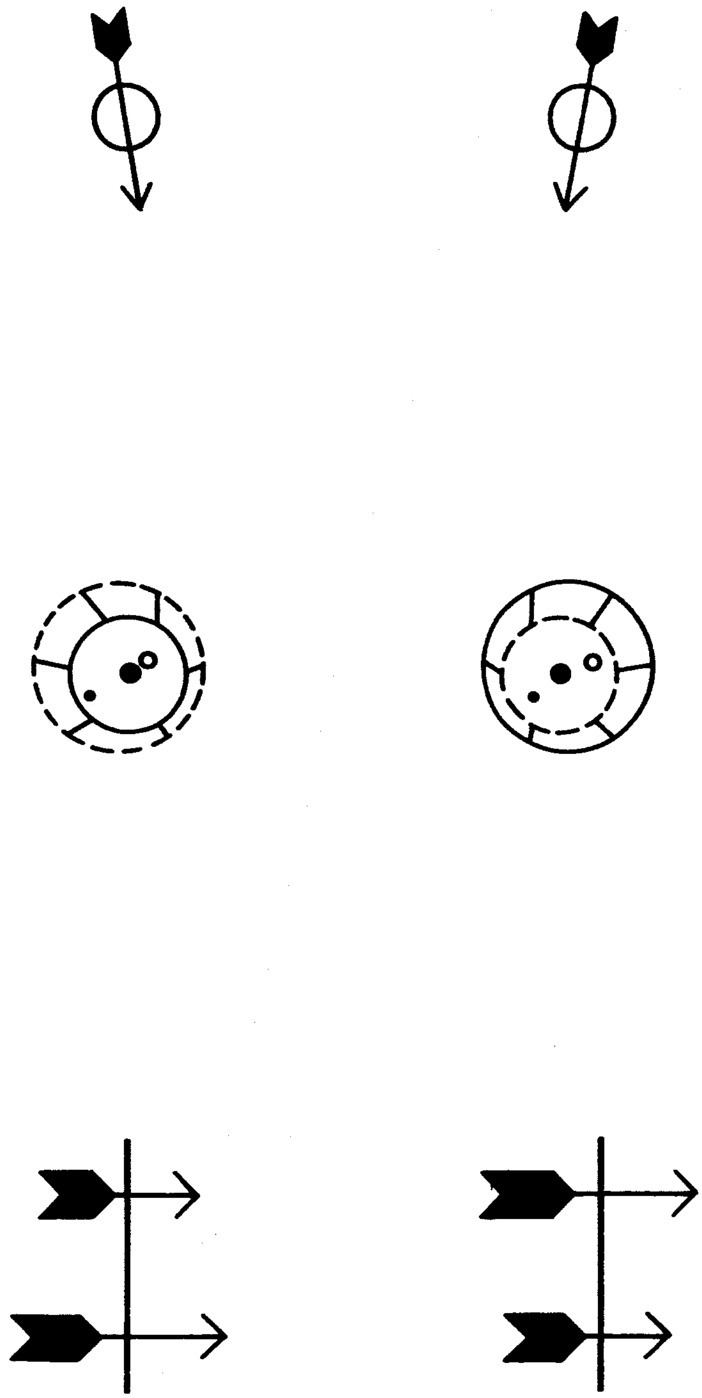


Figure 3-1 Typical Stereograms Used in Subject Screening

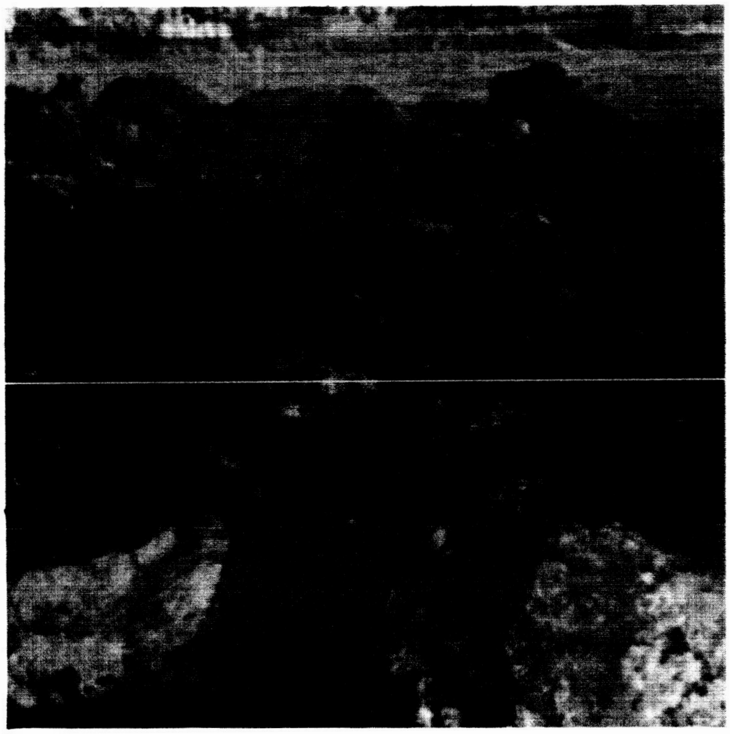


Figure 3-2 Simulated Lunar Surface (Slag)

Pilot test stereogram: Baseline = 3 inch parallel, Camera Height = 42 inches
Field of View = 53°H x 39°H, Camera tilt angle = 30°

Figure 3-3 Typical Stereogram, Simulated Lunar Scene

Pilot test stereogram: Baseline = 3 inch parallel, Camera Height = 42 inches
Field of View = 53° H x 39°H, Camera tilt angle = 30°
Range intervals = 3 ft, Distance to first visible range line = 3 ft,
Path width = 4-1/2 ft

Figure 3-4 Typical Stereo Persfective Grid

The special mounting fixture included a rack and pinion arrangement which permitted the single TV camera to be moved as much as 5 inches left or right from a zero position. A protractor permitted accurate setting of convergence angles. The camera mounting is shown in Figure 3-5. Since the convergence angle pivot point was not at the nodal point of the lens, an allowance for baseline offset based upon the tangent of the convergence angle was necessary. This allowance was only approximated in the pilot experiment.

Two brief experiments were conducted using photos from the pilot experiment. The first was concerned with the relation between stereo baseline and ease of viewing for scenes similar to those to be used in the main experiment. Its purpose was to guide the selection of two stereo baseline conditions to be used in the main experiment. Two measures of performance were used in this test; a time measure and subjects' opinions regarding ease of viewing. In both cases parallel baseline views were better (faster to fuse and easier to view) then convergent baseline views. As anticipated, subjects found that the shorter baseline views afforded better visual comfort than the longer baseline views. Although several subjects expressed difficulty with the 10-inch parallel baseline view, enough could view it satisfactorily to permit its use in the main experiment. Thus it was decided to use 3- and 10-inch parallel baselines in the main experiment. These results are considered applicable only to the main experiment and not necessarily to the design of the SLRV cameras. A discussion of factors related to camera baseline and convergence is contained elsewhere in this section.

The second experiment of the pilot study was used to explore the ability of subjects to correctly relate the simulated lunar scenes with superimposed scaling grids. Grids were presented stereoscopically via a reflex mirror attachment added to the Keystone stereoscope. The grids were laid out on a flat floor and photographed with the same camera viewing geometry as was used for the simulated lunar scenes. Thus, any geometric distortions in the images of the simulated lunar scenes were also reproduced in the scaling grids. Grids were presented to each subject for each of three baseline conditions; 3 inch parallel, 3 inch convergent, and 10 inch parallel. Each baseline condition in turn included grids of two different heights with respect to the simulated lunar surface and these, in turn, were presented at each of two different contrast levels. The "low" grid was in a horizontal plane passing through the base of the TV camera

Figure 3-5 Camera Mounting for Development Tests

tripod as the simulated lunar scene was viewed. The "high" grid was in a horizontal plane 7 inches above the "low" grid. Figure 3-6 shows a profile view of these conditions. One of the contrast conditions was a "bright" grid in which the lines of the grid were as bright as the highlights of the simulated lunar scene. The other contrast condition was a "dim" grid in which the lines of the grid were barely visible and faded out completely about halfway back in the scene.

Three points in the scene were marked by colored dots. Each subject was asked to make a qualitative judgement of the elevation of these dots with respect to each of the 12 test grids. Judgements were in the form of, "dot is below, or in, or above the plane of the grid". These judgements were then transformed to a numerical rating in accordance with the following scale:

Way below	= -3
Below	= -2
Slightly below	= -1
In the plane of the grid	= 0
Slightly above	= +1
Above	= +2
Way above	= +3

Results of this evaluation are shown in Table 3-1. Subjects' comments, which were stimulated only by a general invitation to comment, are summarized in Table 3-2.

Since there was no geometric difference between the "bright" grid and the "dim" grid, theoretically there should have been no difference in their perceived height. However, there was a significant difference. The "bright" grid was perceived higher above the surface than the "dim" grid. Actually this difference was expected; informal observations of the experimenters prior to the test indicated that a bright grid was frequently perceived above all objects in the scene regardless of its correct geometric

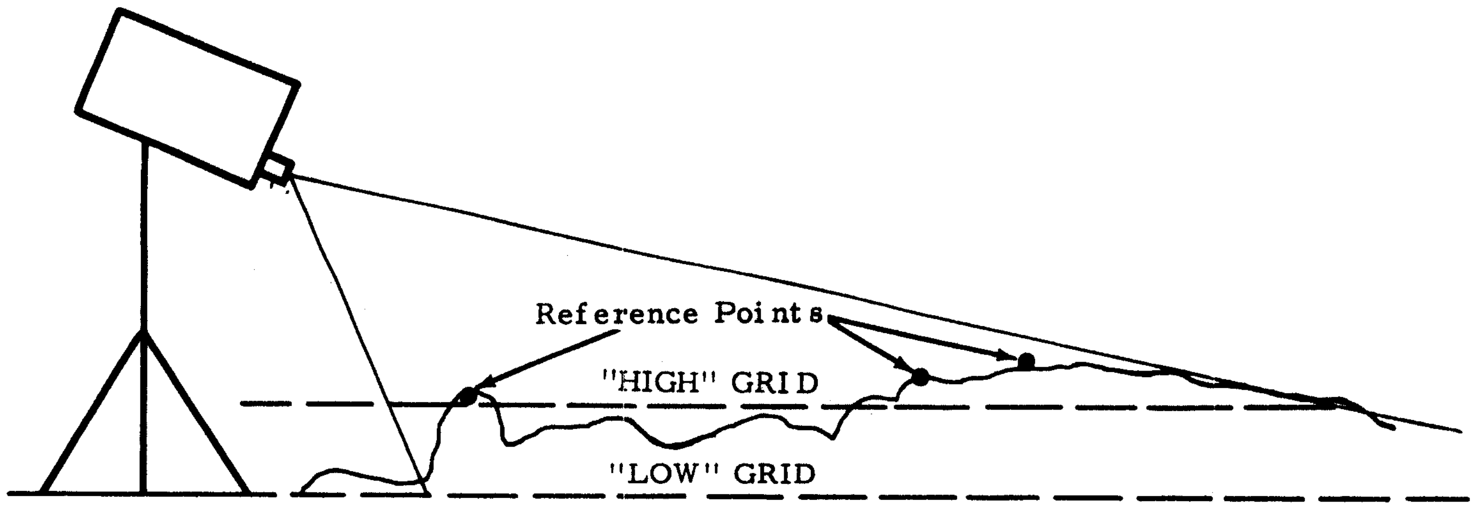


Figure 3-6 Profile View of Geometry for Second Pilot Experiment

TABLE 3-1

RESULTS OF SECOND PILOT EXPERIMENT

(Perception of Stereo Grid Overlay)

Condition	Number of Trials	Mean Perceived Height of Dots Above Grid
Grid Brightness:		
Bright	270	0.67
Dim	270	1.16
Grid Height:		
High	270	1.18
Low	270	0.65
Stereo Baseline:		
3-inch Parallel	180	1.07
3-inch Convergent	180	0.81
10-inch Parallel	180	0.87
ALL	540	0.91

TABLE 3-2

SUMMARY OF SUBJECTS' COMMENTS ON PERCEPTION OF STEREO GRID OVERLAYS

"Dim" grid condition; Comments related to grid visibility
10 of 15 subjects made negative comment (grid too dim, etc.)
4 of 15 no comment
1 of 15 liked dim grid
"Bright" grid condition; Comments related to grid visibility
6 of 15 made positive comments (grid easy to see, etc.)
9 of 15 no comment
3-inch parallel baseline; Comments related to ease of viewing
6 of 15 made negative comment (hard to fuse grids, not clear, etc.)
6 of 15 no comment
4 of 15 made positive comment
(NOTE: One subject made both positive and negative comment.)
3-inch convergent baseline; Comments related to ease of viewing
2 of 15 made negative comment
10 of 15 no comment
3 of 15 made positive comment
10-inch parallel baseline; Comments related to ease of viewing
9 of 15 made negative comment
5 of 15 no comment
2 of 15 made positive comment

TABLE 3-2 (CONT.)

	All conditions: Comments related to spatial perception of grid.
S_1	Left side of grid appears higher (3CLB*)
S_2	—
S_3	Cannot tell (10PLB); Hard to tell (10PLD)
S_4	Grid seems down under rocks in all cases; 3 inch C looks best, grid extends farther out.
S_5	—
S_6	Looks like all rocks above grid (3PHD); Grid looks tipped down (10PHB)
S_7	—
S_8	—
S_9	Grid is perceived below rocks when space in dashed grid is adjacent to rock.
S_{10}	—
S_{11}	Grid looks under ground at right (3PLB); hard to establish plane of grid (3CHB)
S_{12}	—
S_{13}	Difficult to get height perception on yellow point (extreme foreground).
S_{14}	White grid lines look above black rocks but below white rocks. Height of grid looks different in different parts of picture. Needed to study picture to make judgement.
S_{15}	All rocks above grid (3PLD); Not too good, grid buried in rocks (10PHD), Grid plane rolled to right (10PLD), Grid seems to run through rocks which disturbs 3D perception.

*Code indicates condition at which comment was made; i.e., 3CLB means 3-inch convergent, low, bright.

location. Fortunately this extreme condition, which would be indicated by a score of +3, did not materialize in the formal experiment and, presumably, is not a typical situation. Both the numerical results and the comments suggest that the interposition cue to space perception cannot easily be reversed by a steroscopic cue. It was concluded that grid overlays should be no brigher than absolutely necessary for perception to minimize the tendency to perceive them above their proper geometric location.

A comparison of results between the two grid heights should show a significant difference. This indeed was the case. The results, however, are in the wrong direction as a comparison of Table 3-1 and Figure 3-6 will show. For some reason the two grids were, on the average, perceptually reversed in height.

Likewise, no explanation is available for the large difference in perceived height between the 3-inch parallel and the other two baseline conditions.

In general, this second pilot experiment indicates that the utility of a reference grid, even in stereo, should not be taken for granted. It is possible that a grid is useful only on a generally flat surface, in which case a monocular grid would suffice. Monocular grids have been tried informally on the slag scenes, and appear as good if not better than stereo grids. Considerable experimental research is still required to determine the best type and method of presentation of grid overlays. Further discussion concerning the use of scaling grids is contained in the discussion of results of main experiment. .

3.1.5 Main Experiment

3.1.5.1 Experiment Design

The subject's task selected for use in the main experiment was to judge the linear distance between specified points, the inclination with respect to a horizontal plane of a line connecting those points, and the horizontal distance from the camera station to the midpoint of this line. This task is correlated with the actual surface assessment task in that they both require an interpretation of surface geometry. The task is independent of any vehicle design, and because it is specific and clearly defined, it was expected to be learned faster than surface assessment relative to a particular vehicle. Also, correct answers were more easily obtained, and to a higher confidence, than answers to surface assessment relative to a vehicle. Finally, the task was expected to be as sensitive or more sensitive than relative surface assessment for comparing performance with various combinations of viewing system design alternatives and other controlled conditions.

Controlled variables used in the experiment are shown in Table 3-3. The 0-inch camera baseline condition was chosen to simulate monocular viewing, the 3-inch condition approximated the subject's interocular distance, and the 10-inch condition represents the required baseline for mapping based upon Phase I analysis. The two camera heights selected represent the minimum and maximum heights for a practical vehicle design. Scaling grids used in the experiment were similar to the one previously shown in Figure 3-4. They were defined as "plain" simply to distinguish them from some experimental grids containing side sticks and shading which were tried but not used. "Full" resolution was the maximum available from the 525-line closed-circuit TV system used to produce the optical images of the surface. This system provided 400 TV lines horizontal resolution and 375 TV lines vertical resolution. Nominal "1/2" resolution was produced by using only one field of the 2:1 interlaced format and degrading horizontal resolution by means of a shunt capacitor on the video. The resulting resolution as measured with a RETMA TV test chart was 350 TV lines horizontal resolution of 350 TV lines vertical resolution. This failure of the vertical resolution to be degraded by a factor of two (on the basis of the test chart) when one-half of the scan lines were eliminated is believed to be associated with the relationship between scan line width and spacing (line pitch). Neither the camera nor monitor line widths were defocused to provide flat field scanning.

Sun angles listed in Table 3-3 are referenced to the horizontal and were limited by the time of the year and latitude of the test course. The higher angle was the maximum angle available.

Features selected for stimulus conditions were based upon the anticipated mobility capability for a 150-lb vehicle. Stimulus features were distributed with regard to range from the camera station, orientation of the length of the feature, and size of the feature. Radial features were intended to be related to vehicle crevice crossing capability and had lengths ranging from 14 to 46 inches. The inclination of radials ranged from $+56^{\circ}$ (pitch up) to -19° (pitch down). Tangential features were intended to be related to vehicle side clearance capability and had lengths ranging from 7 to 43 inches.

TABLE 3-3

CONTROLLED EXPERIMENTAL VARIABLES

Parameter	No. of Conditions	Values
Stereo Baseline	3	0", 3", 10"
Camera Height	2	36", 48"
Scaling Grid Overlay	2	None vs plain
Resolution	2	"Full" and "1/2"
Sun Angle	2	30° and 13°
Range of Feature from Camera	3	0'-6',6'-12',12'-18'
Orientation of Feature	3	Radial, tangential, vertical
Size of Feature	3	(Dependent upon orientation)
Number of Different Scenes	5	

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The inclination of tangentials varied from +42° (roll right) to -47° (roll left). Radials and tangentials had azimuth offsets up to 45° from nominal. Vertical features were intended to be related to vehicle step climbing capability and undercarriage clearance and had lengths ranging from 5 to 24 inches. Verticals were inclined 56° to 90° from horizontal.

Five different scenes were selected on the test course to provide different sun/line of sight phase angles as well as different scene geometries. Three of the five camera stations were on rises so that the foreground sloped down hill.

Factors which could influence performance in the experiment but which could not be accommodated as controlled variables in the available time period were held constant. Fixed conditions are shown in Table 3-4. The selected field of view was chosen to be similar to the Phase I recommendation of 50°. Field of view was not explored as a controlled parameter since it could not easily be controlled without confounding it with resolution and the stimulus set. Camera tilt angle was selected to cover the desired stimulus range intervals with the selected field of view and two camera heights.

Parallel cameras were selected on the basis of the pilot test results. The illumination type (sun on clear day) together with adjustment of the TV contrast and brightness controls produced optical images approximately simulating the high contrast conditions expected on the lunar surface. Foundry slag was selected to simulate the texture and photometric properties of a rough random lunar surface devoid of familiar size cues. The simulated surface was the same used in the pilot tests as shown in Figure 3-2.

The experimental design selected was basically a factorial design with one subject per each viewing geometry and scaling grid condition for a total of 12 subjects. This design was selected over a subjects-by-treatment design to keep the size of the experiment within manageable bounds and to avoid transfer of training problems associated with subjects switching from one camera geometry condition to another. Other controlled conditions were distributed randomly throughout the stimulus set. The resulting design was complex, lacked precision on higher order interactions, and precluded a formal analysis of variance treatment of the results. Nevertheless it was considered the best approach within the scope of the interim study to gain insight into the problems associated with performing surface assessment by means of operator judgement.

TABLE 3-4

FIXED EXPERIMENTAL CONDITIONS

Camera Field of View	53° H x 38° V
Camera Tilt Angle	-30°
Camera Roll Angle	0°
Camera Convergence Angle	0° (Parallel)
Illumination Type	Sun through clear sky
Terrain Type	Random slag

3615-32

3.1.5.2 Equipment and Stimulus Data Collection

The general test procedure was to have the subjects view stereograms produced from photographs of TV images of the simulated lunar surface. Equipment used was identical to that used in the pilot tests (see Section 3.1.4). Grid photographs were also produced in the same manner and were superimposed on the simulated lunar surface scenes by means of a reflex mirror attachment added to the stereoscope.

The experiment design required production of 120 stereograms distributed between the camera baseline, camera height, resolution, sun angle, and scene conditions. This yielded 20 stereograms per subject. Stimulus features were identified by marking the slag surface with white tape. Two marks producing a data point pair defined a feature. These data points showed up as white dots in the stereograms and were overlayed with colored ink. Since each stereogram could accommodate four pairs of color-coded data point pairs, and to obtain a reasonable number of stimulus values for each combination of stimulus conditions, it was decided to obtain approximately 80 sets of data points. Actual values of distance between, inclination, and distance to each data point pair were made on the slag surface. A total of 82 data point pairs were collected and used in the experiment with the distribution of actual values approximately flat over the desired range of values.

3.1.5.3 Subject Assignment

Subjects were assigned conditions in the main experiment based upon their performance in the stereo screening and pilot tests. Subjects assigned to the wide (10-inch) baseline had "good" stereo ability and further showed no difficulty in fusing and achieving stereopsis with this baseline. Subjects assigned to use the scaling grid were those who indicated little or no difficulty in simultaneous fusion of the grid and the surface and further showed evidence of perception of the grid in proper geometric relation to the surface during the second pilot test. Subjects assigned to the simulated monocular viewing condition (0-inch baseline) had scored "fair" in the stereo screening test and typically had difficulty with one or more of the stereo baseline conditions in the pilot tests.

3.1.5.4 Testing Procedure and Scoring

Subjects were instructed in the objectives of the experiment, test procedure, judgements required, and the camera geometry they would be using throughout the test. Camera geometry was described by illustrations indicating horizontal and vertical fields of view, camera tilt angle, and camera height. Approximate range scaling in the view assuming a flat surface was mentioned but it was pointed out that the surfaces which they would be viewing were generally rough and that flat surface scaling could produce large judgement errors. The scaling of the grid overlay was explained to those who used it. Subjects were not told what baseline condition they would have, except that the 0-inch baseline group was told they would have a relatively narrow baseline and they might find stereopsis a little weak.

Instruction in the test procedure, the judgements required, and explanation of the three orientation categories was provided through the use of three instructional trials on a practice stereogram. The data points of interest for each trial were pointed out with the stereogram out of the stereoscope. This procedure was necessary to ensure that subjects were using the correct pair of data points for the judgements. Subjects were told that finding the correct data points was not a part of the experiment and they should ask to have them pointed out again if they were in doubt about which ones to use.

Subjects were required to make the three required judgements in each trial always in the same order: (1) distance between, (2) inclination, and (3) distance to midpoint. Correct answers were given after each judgement; thus the subjects had the opportunity to adjust their inclination judgement on the basis of the correct distance between. Likewise, subjects could adjust their distance to midpoint judgements on the basis of both the correct inclination and distance between. This procedure was intended to speed up the learning process that was expected to occur and to minimize testing time. The procedure should be modified if experienced subjects are used in future experiments.

The 82 trials were divided into 4 sessions for each subject. Subjects were allowed to work at their own speed. As a result the tests sessions were typically about 30 minutes in length. The order of presentation of trials (data point pairs) was random but the same random order was used for all 12 subjects.

Results of the experiment were scored on the basis of the subject's error on each judgement. Error was taken as the judged value minus the actual value. The arithmetic mean and standard deviation of error scores were computed for various groupings of the data. Tests for normality were not made. Percentage error scores, defined as the ratio of numerical error to actual value, were computed on a per subject basis for distance between and distance to midpoint judgements. An inspection of the percentage error scores indicates that they are generally unreliable as an indication of general performance. Small numerical errors on small actual values frequently yield very large percentage errors. Percentage errors were not computed for inclination scores because many of the actual values were 0° and percentage error would be meaningless. Percentage error scores might have more meaning if results could be partitioned according to size of the actual value. Time was not available for this type of partitioning.

3.1.5.5 Results

The overall results of the surface assessment experiment for each of the three types of judgements are shown in Table 3-5. Individual subject performance, however, varied considerably from the overall group mean performance. This variability both within and among subjects is reflected in Tables 3-6, 3-7, and 3-8, and Figures 3-7, 3-8, and 3-9, which show individual subject performance for both the total experiment and the second half of the experiment on each of the three judgements. In each of these tables and figures, subjects are listed in order of increasing standard deviation of error on total performance. Order rankings based upon other parameters such as percent error or number of gross errors show only approximate correlation to the order ranking based on standard deviation of error. The same is true of the correlation between performance on the second half of the experiment and overall performance. This lack of correlation in order ranking between second half and total performance is an indication of variability within individual subjects. Variation among subjects is reflected in the approximately two-to-one ratio between best and worst performance. In addition, it is noted that a subject's performance on this experiment was not well correlated with his performance on the stereo screening test. Apparently good stereo acuity by itself is not a reliable indication of ability to make quantitative surface assessment judgements. The inverse is also apparently true, although to a lesser extent; that is, lower performance on the stereo screening test does not necessarily correlate with poorer performance on the quantitative surface assessment task.

TABLE 3-5

OVERALL GROUP PERFORMANCE–
SURFACE ASSESSMENT EXPERIMENT

Performance Measure	N*	Error		% Error	
		Mean	S.D.**	Mean	S. D.
Distance Between	982	1.7 inches	10.9 inches	15.7	62.3
Inclination	982	0.5°	20.8°	--	--
Distance to Midpoint	982	-3.3 inches	23.6 inches	-2.1	20.2

* Number of Trials.
** Standard Deviation of Error.

Of some practical importance is the ability to identify those subjects having consistently superior performance. The results suggest that this selection is not easily made. Only 2 of the 12 subjects were among the top 6 subjects in all three performance measures for both total and second half performance. The next best selection is to note that the same 6 subjects were found distributed in the top 6 for second half distance-between judgements and both total and second half inclination judgements. These six subjects are 1, 3, 2, 4, 6, and 11. This superior group of subjects was used in some of the comparative analyses to minimize the data reduction task.

Table 3-9 summarizes the degree of overall learning exhibited during the experiment. Significant learning took place on the two distance judgement tasks but not on the inclination judgement task. This learning was not consistent for all subjects, however. An inspection of Figures 3-7, 3-8, and 3-9 shows that two subjects exhibited essentially zero or negative learning on distance between judgements, five exhibited negative learning on inclination judgements, and one exhibited negative learning on distance-to-midpoint judgements.

TABLE 3-6

DISTANCE-BETWEEN JUDGEMENT PERFORMANCE

Subject	Condition			Total Performance						First Half Performance				Second Half Performance			
					Error (inches)		% Error				Error (inches)				Error (inches)		
	Baseline, Inches	Height, Inches	Grid	N*	Mean	S. D.≠	Mean	S. D.	Number of Gross Error**	N	Mean	S. D.	Number of Gross Errors	N	Mean	S. D.	Number of Gross Errors
1	10	48	No	82	-2.9	6.7	-7.0	33.2	10	41	-2.2	7.4	5	41	-3.6	5.9	5
2	10	36	No	81	1.1	8.5	14.0	54.7	12	40	2.4	9.5	6	41	-0.2	7.7	6
3	3	48	Yes	82	2.5	8.5	17.8	47.7	15	41	3.2	10.3	8	41	1.8	6.2	7
4	3	48	No	82	0.8	8.7	10.2	48.0	15	41	2.7	9.2	9	41	-1.1	7.7	6
5	0	48	No	81	-0.4	9.3	4.7	37.8	14	41	-0.5	9.8	8	40	-0.2	8.9	6
6	3	36	Yes	82	3.4	9.6	16.6	36.0	20	41	5.9	10.6	13	41	1.0	7.8	7
7	0	36	Yes	82	-1.6	10.6	3.1	58.5	16	41	-0.3	11.1	11	41	-2.9	9.9	5
8	10	48	Yes	82	1.9	10.8	8.7	51.2	21	41	-0.1	12.8	13	41	2.0	8.7	8
9	0	36	No	82	0.1	11.4	22.2	93.0	18	41	1.0	11.1	11	41	-0.7	11.6	7
10	0	48	Yes	82	2.2	12.6	17.0	72.5	24	41	3.9	12.4	14	41	0.4	12.5	10
11	3	36	No	82	5.8	13.4	24.7	50.4	21	41	9.8	16.6	18	41	1.8	7.2	3
12	10	36	Yes	82	7.8	13.6	55.7	100.	31	41	8.6	15.7	17	41	7.0	11.2	14
Total				982	1.7	10.9	15.7	62.3	217	491	2.9	12.1	133	491	0.4	9.4	84

*Number of trials
**Errors greater than ± 50% of actual value
≠Standard Deviation of Error

TABLE 3-7

INCLINATION JUDGEMENT PERFORMANCE

	Condition			Total Performance				First Half Performance				Second Half Performance			
					Error (degrees)				Error (degrees)				Error (degrees)		
Subject	Baseline, inches	Height, inches	Grid	N*	Mean	S.D.≠	Number of Gross Errors**	N	Mean	S.D.	Number of Gross Errors	N	Mean	S.D.	Number of Gross Errors
3	3	48	yes	82	4.3	13.3	0	41	5.0	11.9	0	41	3.7	14.5	0
4	3	48	no	82	3.3	15.2	0	41	3.9	13.7	0	41	2.7	16.7	0
6	3	36	yes	82	1.0	16.0	2	41	1.4	17.5	1	41	0.5	14.3	1
2	10	36	no	81	5.5	16.1	1	40	6.2	17.3	1	41	4.8	14.8	0
11	3	36	no	82	3.1	17.2	2	41	3.1	18.5	2	41	3.1	15.8	0
1	10	48	no	82	2.9	20.2	5	41	5.0	23.4	4	41	0.7	15.9	1
12	10	36	yes	82	-0.9	22.0	6	41	-1.2	23.8	4	41	-0.6	20.2	2
7	0	36	yes	82	-1.7	22.1	5	41	0.7	16.9	1	41	-4.0	26.0	4
10	0	48	yes	82	2.3	22.6	4	41	5.9	17.5	1	41	-1.2	26.4	3
5	0	48	no	81	-3.9	22.6	6	41	-5.5	17.0	1	40	-2.1	27.2	5
9	0	36	no	82	-9.3	25.9	8	41	-9.7	28.2	6	41	-9.0	23.3	2
8	10	48	yes	82	-0.8	27.0	8	41	-5.3	25.8	5	41	-5.3	25.8	3
Total				982	0.5	20.8	47	491	1.5	20.6	26	491	-0.6	21.0	21

*Number of trials
**Errors greater than ±45°
≠ Standard Deviation of Error

TABLE 3-8

DISTANCE-TO-MIDPOINT JUDGEMENT PERFORMANCE

Subject	Condition			Total Performance						First Half Performance				Second Half Performance			
	Baseline Inches	Height Inches	Grid	N*	Error (inches) Mean	Error (inches) S. D.≠	% Error Mean	% Error S. D.	Number of Gross Error**	N	Error (inches) Mean	Error (inches) S. D.	Number of Gross Errors	N	Error (inches) Mean	Error (inches) S. D.	Number of Gross Errors
1	10	48	No	82	-0.7	14.4	-2.7	11.7	1	41	-4.1	12.5	1	41	2.7	15.3	0
3	3	48	Yes	82	3.7	16.0	2.2	15.1	4	41	4.6	19.3	3	41	2.8	11.9	1
10	0	48	Yes	82	2.4	17.8	2.7	14.6	4	41	1.8	19.8	2	41	3.0	15.5	2
9	0	36	No	82	-0.8	18.7	0.5	18.7	6	41	-2.7	19.6	3	41	1.2	17.7	3
8	10	48	Yes	82	-7.5	18.9	-7.2	15.6	9	41	-10.6	19.7	5	41	-4.3	17.6	4
7	0	36	Yes	82	-0.6	19.7	1.5	16.5	6	41	-1.9	21.9	5	41	0.6	17.1	1
12	10	36	Yes	82	-9.4	20.2	-6.1	15.0	9	41	-13.2	23.4	6	41	-5.7	15.3	3
2	10	36	No	81	-7.7	20.8	-7.7	18.6	8	40	-9.5	23.2	6	41	-5.9	17.9	2
4	3	48	No	82	-1.8	21.9	-2.7	21.0	7	41	-9.2	21.1	3	41	5.7	20.1	4
6	3	36	Yes	82	-1.0	29.6	4.3	29.4	14	41	0.1	35.8	11	41	-2.1	21.6	3
11	3	36	No	82	-15.5	32.7	-13.9	23.8	18	41	-19.3	37.6	11	41	-11.8	26.2	7
5	0	48	No	81	-0.2	34.5	3.6	26.3	13	41	-1.9	42.5	10	40	1.6	23.3	3
Total				982	-3.3	23.6	-2.1	20.2	99	491	-5.5	27.0	66	491	-1.0	19.3	33

*Number of trials
**Errors greater than ± 3 ft
≠Standard deviation of error

Figure 3-7

INDIVIDUAL PERFORMANCE, DISTANCE-BETWEEN

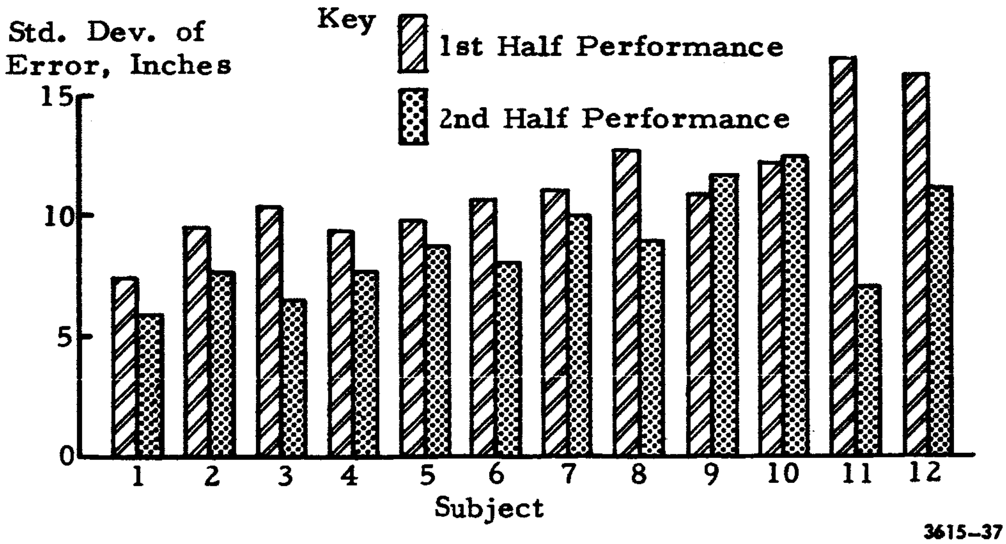


Figure 3-8

INDIVIDUAL PERFORMANCE, INCLINATION

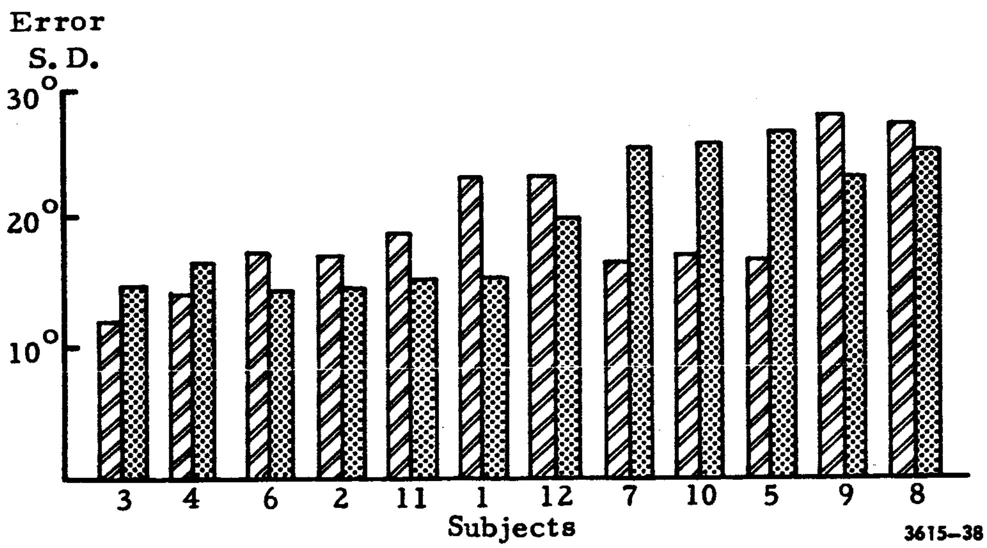
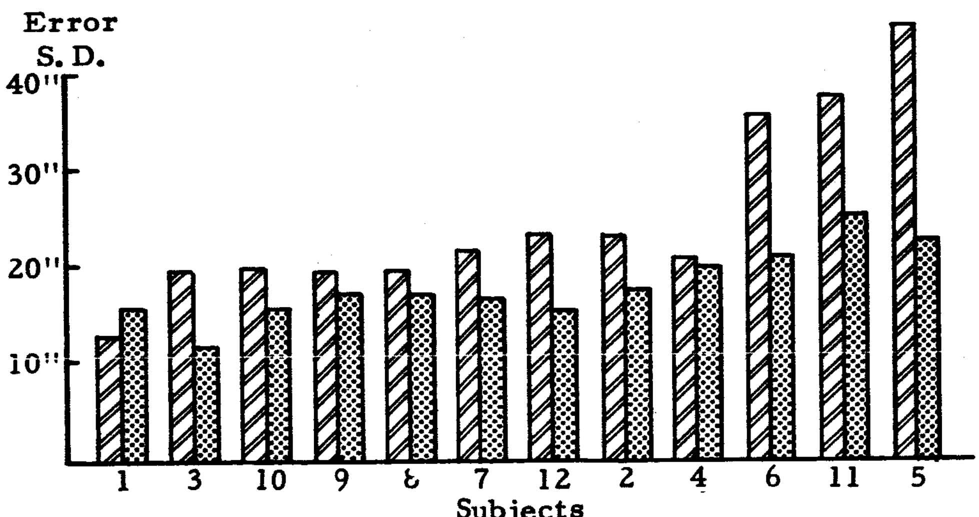


Figure 3-9

INDIVIDUAL PERFORMANCE , DISTANCE TO MIDPOINT



3615-39

The learning reflected in Table 3-9 is total learning and is attributed to a combination of three factors: (1) true learning of the task, (2) learning of the specific geometry of the limited number of scenes in the experiments, which was five, and (3) a bias in the order of presentation of conditions which made the second half of the experiment inherently easier than the first half. This experimental bias is associated with the fact that order of presentation of conditions was randomized rather than counterbalanced. As it turned out this distribution resulted in an overbalance of radial data points in the first half of the experiment and a deficiency of radial data points in the second half. Subsequent analysis of results according to orientation of data points shows that radials are significantly more difficult to judge than tangential and verticals. Another smaller but probable contributing factor to experimental bias was associated with the range of the data points, again the situation being that the first half of the experiment turned out to be inherently easier than the second half.

Results of the experiment analyzed according to stereo base line are shown in Table 3-10 and Figure 3-10. These show that no single baseline condition was superior on all three types of judgement. The three-inch baseline was clearly superior to 10-inch and 0-inch baselines for inclination judgements throughout the entire experiment. For this judgement, 10-inch baseline was a poor second with 0-inch baseline being the worst. For distance-between judgements, the difference in performance as a function of baseline shows up only in the second half of the experiment, there being no essential difference in the first half. In the second half, the 3-inch baseline was superior with 10-inch second and 0-inch third. A significant departure from the general learning trend is noted on the distance-between judgements as a function of baseline. Very little learning existed on the 0-inch baseline condition while the 3-inch baseline condition reflected greater than average learning. However, this pattern of performance vs baseline changes for the distance-to-midpoint judgements where the 10-inch baseline is superior, the 0-inch baseline is second best, and the 3-inch baseline is the worst throughout the entire experiment. Also of interest is the fact that the margin of performance for the 10-inch baseline group was significantly better in the first half of the experiment than in the second half.

Table 3-11 and Figure 3-11 show performance vs the two camera height conditions used in the experiment. Here the trend is small but consistent in favor of the higher camera. This slightly superior performance with the higher camera is evident on the two distance judgement measures while the inclination judgement shows no significant difference with respect to camera height.

TABLE 3-9

PERFORMANCE VERSUS LEARNING
(Based upon all 12 subjects)

Distance-Between Error (inches)				
Trial Set	N	Mean	S. D.	No. Gross Errors
1 + 2	491	2.9	12.1	133
3 + 4	491	0.4	9.4	84
Total	982	1.7	10.9	217

Inclination Error (degrees)				
Trial Set	N	Mean	S. D.	No. Gross Errors
1 + 2	491	1.5	20.6	26
3 + 4	491	-0.6	21.0	21
Total	982	0.5	20.8	47

Distance-to-Midpoint Error (inches)				
Trial Set	N	Mean	S. D.	No. Gross Errors
1 + 2	491	-5.5	27.0	66
3 + 4	491	-1.0	19.3	33
Total	982	-3.3	23.6	99

TABLE 3-10

PERFORMANCE VS CAMERA BASELINE

	Distance-Between Error (inches)											
	0-inch Baseline				3-inch Baseline				10-inch Baseline			
Trial Set	N	Mean	S. D.	Gross Errors	N	Mean	S. D.	Gross Errors	N	Mean	S. D.	Gross Errors
1 + 2	164	1.0	11.3	44	164	5.4	12.4	48	163	2.2	12.4	41
3 + 4	163	-0.8	10.9	28	164	0.9	7.3	23	164	1.3	9.4	33
Total	327	0.1	11.1	72	328	3.1	10.4	71	327	1.7	11.0	74

	Inclination Error (degrees)											
	0-inch Baseline				3-inch Baseline				10-inch Baseline			
Trial Set	N	Mean	S. D.	Gross Errors	N	Mean	S. D.	Gross Errors	N	Mean	S. D.	Gross Errors
1 + 2	164	-2.2	21.4	9	164	3.4	15.7	3	163	3.4	23.6	6
3 + 4	163	-4.1	26.0	14	164	2.5	15.4	1	164	-0.1	20.0	2
Total	327	-3.1	24.0	23	328	2.9	15.5	4	327	1.7	21.8	8

	Distance-to-Midpoint Error (inches)											
	0-inch Baseline				3-inch Baseline				10-inch Baseline			
Trial Set	N	Mean	S. D.	Gross Errors	N	Mean	S. D.	Gross Errors	N	Mean	S. D.	Gross Errors
1 + 2	164	-1.2	27.7	20	164	-6.0	31.0	28	163	-9.3	20.4	18
3 + 4	163	1.6	18.6	9	164	-1.3	21.6	15	164	-3.3	17.0	9
Total	327	0.2	23.6	29	328	-3.6	26.9	43	327	-6.3	19.0	27

Figure 3-10

PERFORMANCE VS CAMERA BASELINE

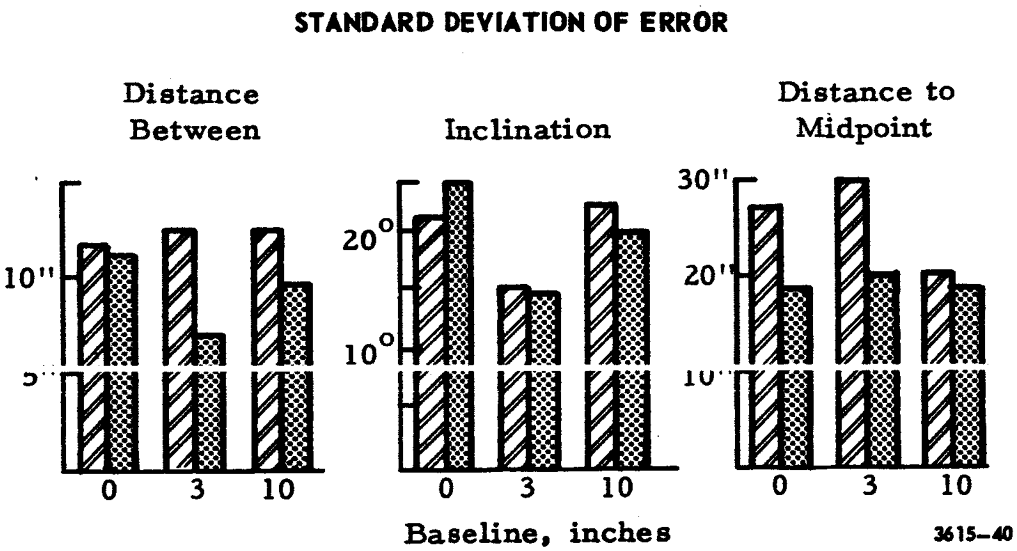


TABLE 3-11

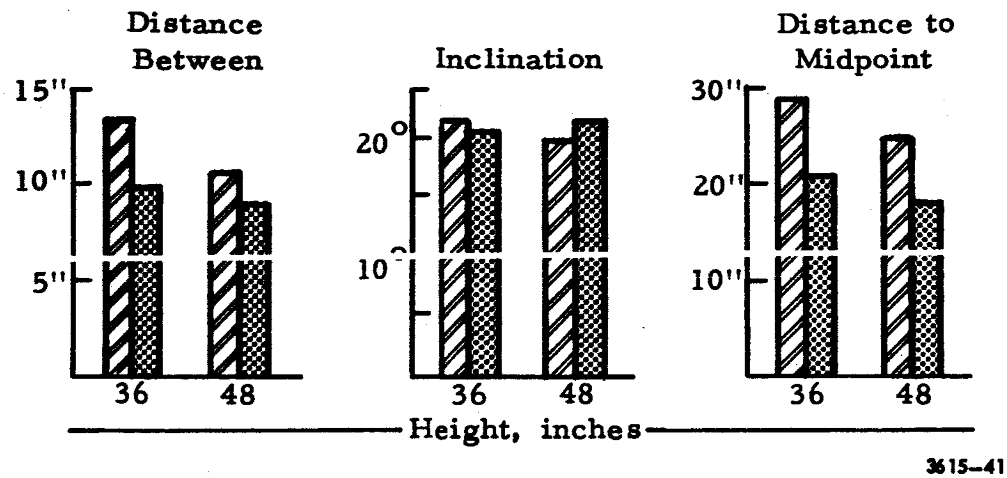
PERFORMANCE VS CAMERA HEIGHT

Distance-Between Error (inches)								
	High (48 inches)				Low (36 inches)			
Trial Set	N	Mean	S. D.	Gross Errors	N	Mean	S. D.	Gross Errors
1 + 2	246	1.1	10.7	57	245	4.6	13.3	76
3 + 4	245	-0.1	8.8	42	246	1.0	9.9	42
Total	491	0.5	9.8	99	491	2.8	11.8	118
Inclination Error (degrees)								
	High (48 inches)				Low (36 inches)			
Trial Set	N	Mean	S. D.	Gross Errors	N	Mean	S. D.	Gross Errors
1 + 2	246	3.0	19.7	11	245	0.1	21.4	15
3 + 4	245	-0.3	21.9	12	246	-0.9	20.1	9
Total	491	1.4	20.9	23	491	-0.4	20.8	24
Distance-to-Midpoint Error (inches)								
	High (48 inches)				Low (36 inches)			
Trial Set	N	Mean	S. D.	Gross Errors	N	Mean	S. D.	Gross Errors
1 + 2	246	-3.2	25.0	24	245	-7.7	28.7	42
3 + 4	245	1.9	17.9	14	246	-3.9	20.2	19
Total	491	-0.7	21.9	38	491	-5.8	25.1	61

Figure 3-11

PERFORMANCE VS CAMERA HEIGHT

STANDARD DEVIATION OF ERROR



Performance versus the use of a plain scaling grid superimposed on the scene is shown in Table 3-12 and Figure 3-12. For distance-between and inclination judgements there is a slight performance margin in favor of the no-grid condition. This tendency is as much evident by the gross error count as by the other measures of performance, the standard deviation and mean. This trend in performance is reversed with distance-to-midpoint judgements. Here the plain grid condition is clearly superior throughout the entire experiment. It is interesting to note that during the course of the experiment some of the subjects who did not have a scaling grid expressed a desire to have one, whereas several of the subjects that had a scaling grid blamed their seemingly poor performance on the fact that the grid was misleading them. A common problem expressed by most subjects using the scaling grid was that it was difficult to extend the necessary imaginary vertical lines from the data points to the horizontal plane of the scaling grid. Subjects were quite aware of the fact that the data points typically did not lie in the plane of the scaling grid but even so found it quite difficult to make correct use of the grids. There was no evidence that they were able to improve in the use of the grids as the experiment progressed.

Table 3-13 shows a partial analysis of performance vs resolution. No significant difference is noted.

Table 3-14 shows a partial analysis of performance vs sun angle. Again there is no significant difference. The absolute values of performances shown in Tables 3-13 and 3-14 should not be compared with performances in other tables without due regard to the limited number of subjects and trial sets used in Tables 3-13 and 3-14.

TABLE 3-13

PERFORMANCE VS RESOLUTION
(Analysis based upon best 6 subjects)

Distance-Between Error (inches)				
Resolution	Trial Sets	N	Mean	S.D.
Full	3 + 4	114	-0.9	7.5
1/2	3 + 4	132	0.7	7.1

TABLE 3-12

PERFORMANCE VS USE OF SCALING GRID

Distance-Between Error (inches)								
	No Grid				Plain Grid			
Trial Set	N	Mean	S. D.	Gross Errors	N	Mean	S. D.	Gross Errors
1 + 2	245	2.2	11.6	57	246	3.5	12.7	76
3 + 4	245	-0.7	8.5	33	246	1.6	10.0	51
Total	490	0.8	10.2	90	492	2.6	11.4	127

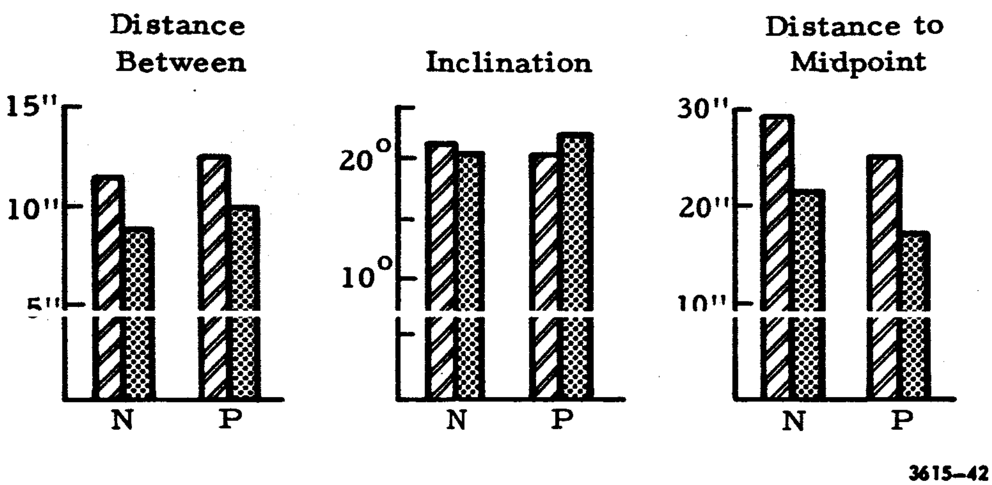
Inclination Error (degrees)								
	No Grid				Plain Grid			
Trial Set	N	Mean	S. D.	Gross Errors	N	Mean	S. D.	Gross Errors
1 + 2	245	0.5	21.2	14	246	2.6	20.0	12
3 + 4	245	0.0	20.0	8	246	-1.2	22.0	13
Total	490	0.3	20.6	22	492	0.7	21.2	25

Distance-to-Midpoint Error (inches)								
	No Grid				Plain Grid			
Trial Set	N	Mean	S. D.	Gross Errors	N	Mean	S. D.	Gross Errors
1 + 2	245	-7.8	28.8	34	246	-3.2	24.8	32
3 + 4	245	-1.1	21.2	19	246	-0.9	17.1	14
Total	490	-4.4	25.5	53	492	-2.1	21.4	46

Figure 3-12

PERFORMANCE VS USE OF SCALING GRID

STANDARD DEVIATION OF ERROR



Key

N = No grid
P = Plain grid

TABLE 3-14

PERFORMANCE VS SUN ANGLE
(Analysis based upon best 6 subjects)

Distance-Between Error (inches)				
Sun Angle	Trial Sets	N	Mean	S.D.
High (30^{o})	3 + 4	120	0.9	7.6
Low (13^{o})	3 + 4	126	-0.9	7.0

Table 3-15 and Figure 3-13 show performance on each of the three judgements as a function of range to the data point. Significant differences are noted with a general tendency of increasing standard deviation with increasing range but with decreasing mean error with respect to increasing range.

Table 3-16 and Figure 3-14 show performance vs data point pair orientation for each of the three types of judgement. This table indicates a very significant difference in distance-between judgements as a function of data point pair orientation. The length of vertical lines can clearly be judged far more accurately than can the length of radial lines with judgements of tangentials being approximately halfway between. Judgement of inclination for tangentials is clearly superior to that for radials and verticals. A similar trend exists for distance-to-midpoint judgements.

3.1.6 Discussion and Conclusions

This experiment was the first step in exploring the accuracy with which the geometry of an unfamiliar surface can be quantitatively assessed by means of an operator viewing an optical image of the surface. ,Many factors which were thought to have possible influence on performance of this surface assessment task were explored in the experiment. The resulting experimental design was very complex and interactions between controlled conditions were confounded. Nevertheless the experiment was useful in indicating the general accuracy with which this task may be expected to be performed and, further, gave an indication of which parameters have the greatest effect on influencing accuracy of performance.

TABLE 3-15

PERFORMANCE VS RANGE

(Analysis Based Upon Best 6 Subjects)

Range	Trial Sets	Distance-Between Error (inches)			Inclination Error (degrees)			Distance-to-Midpoint Error (inches)		
		N	Mean	S. D.	N	Mean	S. D.	N	Mean	S. D.
Near, 0 to 6 ft	1+2+3+4	156	4.3	9.6	156	3.7	14.3	156	-3.1	14.4
Mid, 6 to 12 ft	1+2+3+4	174	1.0	8.0	174	5.6	16.5	174	1.2	24.0
Far, 12 to 18 ft	1+2+3+4	161	0.2	11.5	161	0.5	18.1	161	-9.7	30.1

TABLE 3-16

PERFORMANCE VS DATA POINT PAIR ORIENTATION

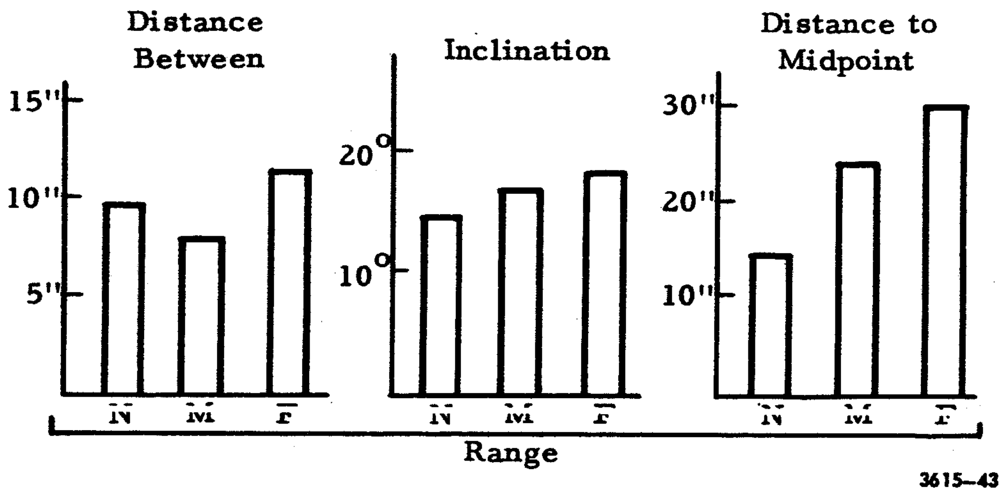
(Analysis Based Upon Best 6 Subjects)

Data Point Pair Orientation	Trial Sets	Distance-Between Error (inches)			Inclination Error (degrees)			Distance-to-Midpoint Error (inches)		
		N	Mean	S. D.	N	Mean	S. D.	N	Mean	S. D.
Radial (Up to 56° Above Horizontal)	1+2+3+4	168	1.[illegible]	12.9	168	9.0	18.0	168	-2.6	26.4
Tangential	1+2+3+4	161	2.[illegible]	9.6	161	1.2	10.1	161	-3.3	21.5
Vertical (Within 34°)	1+2+3+4	162	1.[illegible]	5.7	162	-0.5	18.3	162	-5.4	24.0

Figure 3-13

PERFORMANCE VS RANGE

STANDARD DEVIATION OF ERROR



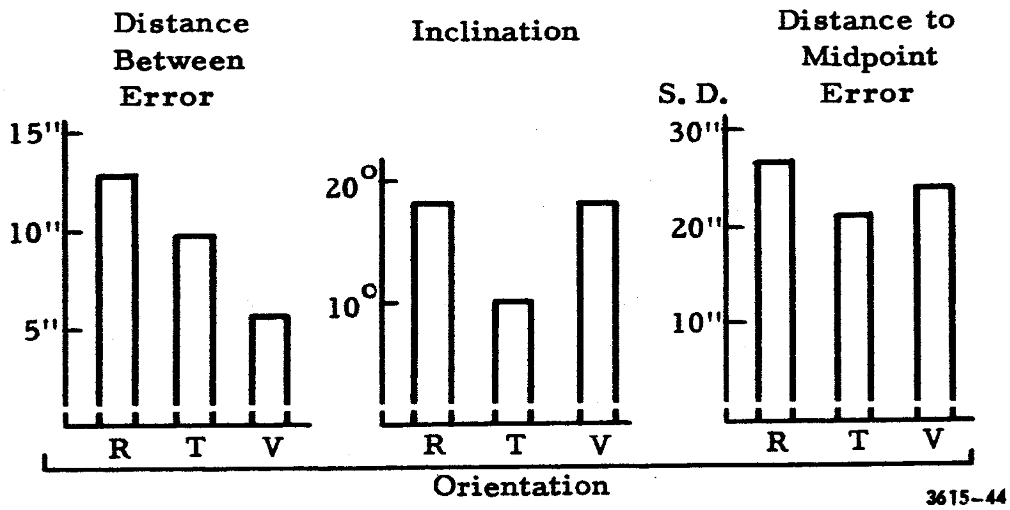
Key

N = near 0'-6'
M = mid 6'-12'
F = far 12'-18'

Figure 3-14

PERFORMANCE VS ORIENTATION

STANDARD DEVIATION OF ERROR



Key

R = Radial
T = Tangential
V = Vertical

On an absolute basis, the overall performance was poor, especially if the values obtained are to be taken as an indication of the necessary safety factor with respect to traversing discrete features such as slopes, steps, or crevices. For example, if the accuracy with which a radial line can be estimated is used as an indication of the accuracy of estimating the width of a crevice, then a safety factor of over two feet would have to be applied to the vehicle's crevice crossing capability for only a 95% probability of safe crossing. Similarily the safety factor for 95% probability of success for step climbing, based upon accuracy of judging the length of verticals, would be on the order of one foot, and slope climbing based upon performance of even the best subject on inclination judgments would require a safety factor of over 26° for 95% probability of success. These analogies may not be completely correct but they give an indication of the general magnitude of the problem. Unfortunately these large errors are considered typical and correlate well with the results of a similar experiment conducted during the vehicle test program in which observers made judgments of size, distance, and slope while directly viewing a stereo TV image. (This other experiment is described in Section 2.2.) The general conclusion to be drawn is that quantitative surface assessment by operator judgment is, with present procedures and viewing apparatus, grossly inaccurate. The remainder of this section is devoted to discussion of the various factors that influence the judgment of surface geometry and suggestions for improving performance on the surface assessment task.

The results indicate that surface geometry itself has a considerable influence on the accuracy of judgments perhaps greater than any of the imaging system design factors explored in the experiment. Large differences in performance are associated with data point pair orientation and smaller but significant differences in performance are associated with the range of the data point pairs from the camera station. It is believed that large difference in performance would also be found as a function of the surface gross slope characteristic. The five camera stations used in this experiment were generally similar in that they all were viewing a generally flat (but rough) scene. In three cases the camera was located on a slight rise so that the slope in the immediate foreground was pitched down. However, in general, all scenes subtended approximately the same ranges. This would not be true if there was a large scale slope gradient in the scene; for example, if the surface pitched up abruptly in front of the camera the range subtended by the vertical field of view would be much less. Introducing such gross slope changes into the characteristics of the unknown scenes can be expected to make performance even poorer than that shown in this experiment. This condition would be further aggravated if camera pointing angles were not standardized as they were in this experiment even though the observer may have a numerical knowledge of such angles.

3.1.6.1 Camera Baseline Conclusions

Performance vs camera baseline leads to the general conclusion that a stereo imaging system would be somewhat better than a monocular imaging system for quantitative surface assessment judgments. (Performance with a monocular system is reflected by the zero-inch baseline condition.) The amount of improvement in performance associated with stereo imaging as well as the best stereo camera baseline are questions not clearly answered by this experiment. A part of this problem is believed to be associated with the fact that while a camera baseline greater than the observer's interocular separation (approximately 2-1/2 inches) increases his ability to discriminate small differences in distance between objects, it also increases the overall distortion of the scene so that absolute magnitudes of distance and slope are distorted. An additional problem in this experiment is that observers were not viewing the image from the center of the perspective, but were somewhat behind the center of perspective. Theoretically this viewing position should tend to elongate the scene with this distortion being more noticeable with the larger camera baseline.

The human visual system is incapable of operating as a range finder, determining the range to a single point by noting the angles of incidence of light rays to that point from each of the two eye positions. Rather, the human perceives a visual scene as a whole using many cues in a complex manner. The binocular disparity cue provided by a stereo imaging system aids in the perception of depths by establishing the relative separation of objects within the scene. This sensation of relative separation due to stereopsis can be exaggerated over that of normal experience by a camera separation greater than interocular distance or can be reduced by a camera separation less than the inocular distance. An image scene correctly scaled in all dimensions will have angles identical to those in the original object scene. The results show that the 3-inch baseline group had the lowest standard deviation of inclination error by a very significant amount.

The absolute scaling of an image scene is controlled primarily by monocular cues established by camera field of view, height, and pointing angles. However, unless the observer views the image from the center of perspective, the scale factor varies as a function of range. Only if the observer is at the center of perspective does the same scale factor apply throughout the scene and at this point the scale factor is unity. That is, all images subtend the same angle to the observer as the corresponding objects would if the observer were located at the camera position.

The apparent distance to the image scene as a whole for a stereoscopic image is primarily a function of camera convergence angles. If cameras are parallel (zero convergence), then the image scene will be perceived between the observer and the display screen. On the other hand, if the cameras are converged in the front of the nearest point in the scene, then the image of the scene will be perceived behind the display screen with the edges of the image forming a window through which the image is seen. Thus if the observer is conscious of the existence of the viewing screen and the distance to that screen, the absolute scaling of distance to various points within the scene can be distorted if camera convergence angles and distance to the viewing screen are not compatible.

An additional distortion occurs when parallel cameras are used. In this case objects at a distance less than infinity lying along the outside edges of the field of view occur in only one of the two images. These points which appear in only one image are perceived with zero parallax and thus are perceived spatially at the maximum distance within the stereo model, or in other words, tend to hang on the viewing screen. This tendency for the outside edges of images taken with parallel cameras to hang in the plane of the viewing screen tends also to distort the location of other nearby image points which, by virtue of monocular cues, are obviously associated with those on the edges.

The apparent large interaction between learning and the camera baseline for distance-between judgments, as reflected in Table 3-10 of the previous section, is of considerable interest. No explanation for this interaction has yet been found and the condition should be explored further in future experiments of this sort. On the basis of arguments previously presented, such an interaction might be expected, but in a completely opposite direction; that is, since the 3-inch baseline provides an image most like that which an observer would have if he viewed the scene directly, then initial performance on the 3-inch baseline should be better than on the other conditions and learning should not be as great as on the other conditions. The results show just the opposite, with initial performance being essentially no different, or with zero baseline being slightly better, followed by considerable and rapid learning for 3-inch baseline and virtually no learning for zero baseline. Learning for the 10-inch baseline group was average for the entire group.

Another puzzling factor is that performance on the basis of gross errors does not keep pace with performance on the basis of standard deviation of errors for the 3-inch baseline. The interaction of learning with baseline is evident primarily on the standard deviation of the error scores and does not show up to the same extent on either mean or gross error scores.

Performance vs baseline on inclination judgments is in accordance with the theoretical concepts previously discussed. Three-inch baseline is by far superior on both standard deviation of error and gross error scores to the other baseline conditions. Also, the zero baseline performance on inclination shows negative learning on both standard deviation of error as well as on gross error count, somewhat reflecting the fact that there is very little basis on which to determine inclinations with zero baseline images. Ten-inch baseline shows positive learning for both standard deviation of error, mean error, and gross error scores; however, the absolute value of performance is not as good as that of a three-inch baseline, reflecting the results of distortion of the geometry of the image scene due to exaggerated stereo baseline.

Performance on the distance-to-midpoint judgment task vs camera baseline shows a rather peculiar trend, not in accordance with the theoretical considerations previously discussed. The trend reflected by standard deviation of error and gross error scores is for the 10-inch baseline performance to be superior throughout the experiment, for 0-inch baseline to be second best, and 3-inch baseline performance to be the worst. However, this trend does not hold for performance on a basis of mean error in which the lowest mean is shown on 0-inch baseline, with 3-inch being second best and 10-inch baseline having the largest mean error. The variations in performance on these distance-to-midpoint scores as a function of camera baseline are smaller than for the other two judgments. The argument might be made that they are associated with the generally large variability among subjects, but the complex experiment design does not permit separating these sources of variability.

3.1.6.2 Camera Height Conclusions

The generally consistent, slightly superior performance associated with the higher of the two camera heights used in the experiment is believed to be associated with a combination of factors. Since the data points were in identical locations in the object scene for both the high and the low cameras, the lower camera tended to crowd these data points into the upper part of the picture format where distances per unit length of image are great. The high camera position, on the other hand, tended to crowd the data points into the lower portion of the format where distances are more accurately estimated. The second factor believed to influence this performance is that radials in the far range interval subtended a smaller angle for the low camera than for the high camera and were more easily partially masked or confused with foreground features than with the higher cameras. These two conditions would tend to suggest that a higher camera will yield better performance.

However, there is a third factor that influences performance vs camera height: that is, the normal height of the observer's eyes when viewing similar scenes. On this basis, performance vs camera height could be expected to deteriorate again as the height is increased considerably above the observer's eye height since the average standing person's eye height is approximately 64 inches. However, this hypothesis has little application to the SLRV program since the maximum height which can be reasonably mechanized is much less than the eye height of a standing observer.

The results show only a small performance trend in favor of the higher camera. This difference is not considered great enough to be the only factor in establishing camera height. Within the existing practical design limits, camera height should be established more on the basis of obtaining the necessary area coverage than on optimizing accuracy of surface assessment. The influence of camera height and position on the vehicle as they relate to obtaining the desired field of view in front of and around the vehicle was explored during the vehicle test program as described in Section 2.

3.1.6.3 Scaling Grid Conclusions

A hypothesis that existed at the beginning of the study program was that a perspective grid stereoscopically superimposed upon an unknown scene and representing a horizontal plane through the ground at the camera station would be a significant aid in quantitative interpretation of scene geometry. As the experimental program progressed, however, and various methods of superimposing grids were tried, confidence in the validity of this hypothesis was greatly diminished. Problems relating to the inability of observers to perceive the synthetic grid in proper geometrical relationship to the terrain were discovered in the pilot experiment. The primary problems are related to the influence of grid to background contrast influencing the perceived location of the grid, the distortion of the plane of the grid as it is pierced by objects in the scene, and the apparent strong influence of the superposition cue which prevents any line element of the grid from being perceived below the surface. (There are later indications to the effect that these perceptual problems are overcome by persons highly skilled in stereoscopic perception.) The grids used in the main experiment attempted to minimize these effects by maintaining as little contrast as possible and by using broken lines in the grid. The results of this experiment led to the conclusion that a plane scaling grid, even though presented geometrically correctly in stereo upon a stereo scene, is of little help in assisting an observer to make correct quantitative judgments of scene geometry. The basic problem regarding the ineffectiveness of the grid seems to be that for a rough or rolling surface the plane of the grid does not coincide with the surface. Proper use of the grid for distance judgments requires the observer to project an imaginary vertical line through the data point and locate its intersection with the scaling grid. Subjects were aware of this requirement but found it difficult to execute.

It might be assumed that since the inclination of the surface was initially unknown, the horizontal grid would aid in judgments of slopes, but this was not the case. There was essentially no difference in performance in inclination judgments as a function of the use of the scaling grid. Although not a controlled experimental condition, observations made during the setup of the experiment suggest that the observers head tilt angle has more to do with establishing a horizontal local reference plane than does the synthetic grid superimposed on the scene. As a result of this informal observation, the stereoscope was adjusted so that the observer's head tilt angle was similar to that of the cameras when the pictures were taken (down 30°). This influence of observer's head angle on slope judgments should be explored in future experiments. A plane scaling grid as used in this experiment might have some greater benefit with respect to no grid if either the gross slope characteristics of the various scenes to be judged vary more greatly from one another than they did in this experiment, or if camera pitch and roll angles are not standardized. The absolute value of performance might deteriorate faster when these complexities are added than could be compensated for by the use of a plane scaling grid. Indeed, if the slope characteristics are such that the grid lies either way above or below some point of the surface, it is expected that observers may find the grid far more distracting than they did even in this experiment, in which several felt that the grid was providing no help and may even have been misleading their judgments.

If the construction of a scaling grid could be modified to allow for various camera angles and could further be modified to allow for surface gross slope characteristics in the scene, then it may be of some considerable assistance to the observer in establishing an absolute scale for the scene. If this were done, the scaling grid would provide essentially a monocular cue, although if presented on a stereo image of the scene it may be necessary also to present the grid stereoscopically. This latter point should be investigated further. Again, informal observations during setup of the experiment explored briefly the effect of monocular vs stereoscopic grid overlays on a stereo scene. The conclusion at the time was that there was little difference between the two and that the monocular grid seemed to be more easily perceived as lying on the surface of the unknown terrain. If a monocular grid could be used, display equipment would be greatly simplified and operator selection and training requirements would be reduced.

Discussion of the use of a synthetic grid has thus far been related to its use as a scaling aid. Similar problems can be expected in the superposition of a synthetic vehicle path, either actual or predicted, on the image of the surface for vehicle control purposes. It is very likely that for such path overlays to be effective, these overlays will have to be corrected not only for camera pointing angles but also for the gross slope characteristics of the scene. This latter requirement means that gross slope characteristics of a scene must be established, probably through photogrammetric profiling, prior to moving the vehicle. The implication of this requirement on ground equipment is discussed in a later section.

3.1.6.4 Optical Resolution Conclusions

The lack of an observed difference in performance due to TV resolution was expected for several reasons. First, the reduced resolution condition did not yield a large reduction in measured resolution on the basis of the resolution test chart. Second, all data points in the object scene were marked large enough that they appeared on the TV image; thus resolution did not influence the detectability of individual data points. Third, the method of marking colored dots on the stereograph with colored ink no doubt detracted somewhat from the better stereoscopic cue theoretically obtainable with the higher resolution. (The colored dots typically were greater than a resolution element in size.) Even if these shortcomings in the experimental apparatus and procedure were not present, resolution in the range considered would still not be expected to have a significant influence on accuracy of quantitative judgments. Resolution, in the vicinity of 200 to 400 TV lines, is not expected to have a significant influence in judging sizes, slopes, or distances in scenes such as those used in this experiment in which features were generally large and sharply defined. The problem in detection of individual features in such scenes seems more associated with obtaining sufficient contrast and in being able to see into shadows than with insufficient resolution. Tests and analyses performed in Phase I with respect to photogrammetry indicated only slight deterioration in accuracy of measuring parallax as the number of picture elements were decreased from 400 to 200. The scenes used in that study also contained large sharp-edged objects.

Resolution could become a major factor if, for purposes of navigation or mission planning, it would be desirable to view objects at long ranges (distances greater than about 25 ft which is the approximate maximum distance of immediate interest to remote control). Resolution may influence control performance, however, as the surface texture becomes fine grain and as features on the surface become more rounded rather than sharp-edged. Indeed, it is believed that a gently rolling fine texture devoid of sharp-edged features will be extremely difficult to assess. In the extreme case, such an area could appear as a vast area of nothing. The only relief in such a situation would be a priori knowledge that hazards do not exist in such an area. Experiments exploring surface assessment capability as a function of sensor resolution should be conducted for fine-textured, smooth-contoured surfaces if there is any possibility that such surfaces might exist on the surface of the moon.

3.1.6.5 Sun Angle Conclusions

As expected, sun angle did not have any significant influence on performance in this experiment. Sun angle determines primarily whether or not a feature is hidden by shadow. Although some of the data points were in shadow areas, the individual data points themselves were made sufficiently bright to be seen. Observers occasionally commented that data points surrounded by large shadow areas were difficult to locate spatially. This condition, however, is attributed not to sun angle per se, but to the fact that large shadows destroy the continuity that would otherwise exist within a scene.

The size and frequency of shadows on the surface is established by a combination of sun angle and surface geometry. Unless the vehicle is equipped with a sensor that can see into shadow areas, making use of earth shine or starlight, or unless the vehicle is equipped with some sort of headlight, it will be essentially impossible to assess the characteristics of a surface within a shadow area. While a rather laborious process of picture measurement and shadow analysis might be able to establish that there is no proturbance above a certain height in a shadow area, there would be no way to assure that there are no hazardous depressions, holes, or crevices in that shadow area. Thus, the appropriate mission strategy would seem to be to stay away from shadow areas large enough in size to include hazardous objects. The extent to which such a mission strategy would increase mission time is a complex question highly dependent upon a very detailed surface model. Such an investigation has not been made in the study program and there is considerable doubt whether anything but a large-scale physical simulation would yield meaningful results.

One of the scenes used in this experiment was so located that the TV camera's shadow was within the scene for one sun angle condition. Although observers were aware of the camera height above the surface, there was no indication that any of them attempted to make use of this shadow information on a known object to aid in their judgments. The only comments made at all regarding the shadow indicated it to be more of a distraction than an aid. Any use of shadows from known objects on the vehicle as an aid in surface assessment would have to be based upon measurement and computation rather than operator judgment. Such computations would probably be more complicated and yield less accurate results than could be obtained from stereo imaging.

The generally large errors in judgment encountered in this experiment as well as in similar tests conducted during the vehicle test program raised the question of whether or not observers would make significantly better judgments if they could view the scene directly with the unaided eye, and whether or not long-term training and experience on tasks requiring stereo perception and judgment would likely improve performance.

The first question was answered by a brief test using one subject on the vehicle test course. Results of this test are reported in Section 2. 2. Although the sample size is extremely small, the trend is quite apparent. Judgments of sizes and distances similar to those used in this experiment made with the unaided eye on the object scene are better than those in this experiment by a factor of approximately 3. This suggests considerable room for improvement in performance.

The remaining question is how to achieve a gross improvement in performance. One readily available solution would be to rely exclusively upon photogrammetric measurements on all points of interest within each scene. Although nothing like a complete contour map would have to be produced for each scene, the process would still be time consuming and increase present estimates of critical ground operation time. Since ground operation time is already a large percentage of total mission time, it is considered desirable to continue to pursue ways of improving operator judgment of surface geometry, leaving photogrammetric measurement as a backup technique. An advantage in relying solely on photogrammetric measurement for surface interpretation is that there would be no question about using the larger stereo baseline. On the other hand, if the majority of surface assessments for purposes of vehicle control are to be established by operator judgment, then evidence to date indicates that a baseline on the order of 3 inches should be used. If both photogrammetric measurement and judgments are to be made from a single stereo imaging system, then some compromise baseline must be found through further experimental research on the influence of stereo baseline on accuracy of quantitative judgments. Table 3-17 illustrates the accuracies which could be expected for the surface assessments made in this experiment if done by photogrammetric measurement. The values were based upon the basic photogrammetric error analysis conducted during Phase I. The distance-between measurements in the far range with a 3-inch baseline were established more accurately by judgment in this experiment than could be expected by photogrammetric measurement.

The generally large errors produced in this experiment raised the question of whether much better performance might be produced by a person with exceptionally good stereo perception and with considerable experience in viewing stereo images. To answer this question, the services of a photogrammetrist with eight years' experience were obtained to take the test. He was given the stereo screening test and the complete main experiment for the conditions of 10-inch baseline, 48-inch camera height,

TABLE 3-17

ESTIMATED EQUIVALENT PHOTOGRAMMETRIC ERROR
(FULL RESOLUTION) – STANDARD DEVIATION OF ERROR

Range	Distance-Between Radials, inches		Distance-Between Tangentials or Verticals, inches		Inclination (Avg Line Length of 25") degrees		Distance to Midpoint, inches	
	3-inch Baseline	10-inch Baseline	3-inch Baseline	10-inch Baseline	3-inch Baseline	10-inch Baseline	3-inch Baseline	10-inch Baseline
Near (3 ft)	1.95	0.58	0.44	0.[illegible]7	1	0.4	1.38	0.41
Mid (9 ft)	17.5	5.25	3.74	1.[illegible]7	8.5	2.7	12.4	3.71
Far (15 ft)	48.7	14.5	10.4	3.[illegible]8	22.5	7.3	34.5	10.3

and plain grid. His performance on the screening test indicated stereo perception ability superior to that of any of the subjects in the original group. His performance in surface assessment is given in Table 3-18. By comparing his scores with those of the original group of subjects (Tables 3-7, 3-8, and 3-9), it can be seen that his performance was not superior to the better subjects in the original group. His performance on distance-to-midpoint judgments is not indicated solely by his numerical scores; most of his judgments were quite accurate but his total score was lowered by a few very large unexplained errors. He also showed no difficulty in correct perception or use of the scaling grid, and thought it was not only helpful but would be essential. However, he had difficulty in establishing the necessary vertical references through the data points, and he thought that one or more vertical reference lines in the scene would help considerably. It is apparent from this test that good stereo perception is not in itself sufficient to produce accurate surface assessment judgments.

3.1.7 Recommendations

Additional experimental research is clearly required to determine the degree to which the accuracy of surface assessment by observer judgment can be improved. This additional research should provide a display apparatus which permits the observer to view the image from the center of perspective. In addition, the next experiment preferably should not require the artificial marking of data points in the object scene. Subsequent experiments should be of less complex design and permit statistical analysis of variance for all interactions. Since absolute accuracy of performance is of as much interest as comparative accuracy on various controlled conditions, further experiments should seek to use only highly qualified and proficient observers as test subjects. Based on the results of this experiment, this latter recommendation is not easily attained. It may be necessary to give subjects extensive tests, such as those used in this experiment, to determine if they are suitable. The experimental procedure of feedback of correct answers should be modified in future experiments by, at least, not providing feedback of correct answers until all judgments within a scene have been made. Eventually, the experimental procedure should require many judgments of many scenes before correct answers are given. The procedure used in this experiment provided feedback of correct answers after each and every judgment. Thus, inclination estimates were occasionally modified on the basis of the correct answer to the distance-between judgment. Likewise, distance-to-midpoint judgments were occasionally modified on the basis of both the correct inclination and the correct distance-between values. If

TABLE 3-18

PERFORMANCE OF EXPERIENCED PHOTOGRAMMETRIST

Data Set	N	Distance - Between Judgments		
		Error (inches)		Number of Gross Errors
		Mean	S. D.	
1st Half	41	0.6	8.9	5
2nd Half	41	0.6	6.9	1
Total	82	0.6	8.0	6

Data Set	N	Inclination Judgments		
		Error (degrees)		Number of Gross Errors
		Mean	S. D.	
1st Half	41	2.8	17.0	2
2nd Half	41	1.1	17.6	0
Total	82	2.0	17.3	2

Data Set	N	Distance-to-Midpoint Judgments		
		Error (inches)		Number of Gross Errors
		Mean	S. D.	
1st Half	41	2.0	22.2	1
2nd Half	41	-2.4	15.2	1
Total	82	-0.2	19.1	2

either of the experimental procedures recommended for future experiments had been followed in this experiment, the performance on inclination and distance-to-midpoint would have been somewhat worse. The initial set of future experiments should use a fixed camera height, fixed camera baseline of 2-1/2 or 3 inches, and no grid overlay. Initial future experiments should be concerned with selection and training of subjects and establishment of the optimum method of image display, where "optimum" pertains to that which maximizes accuracy of surface assessment judgments. After subjects have been selected and trained and the optimum presentation technique established, additional experiments should explore performance as a function of grossly differing scene geometries, the effect of various camera tilt and roll angles, the effect of camera field of view (taking care to maintain the correct observer image-viewing geometry), exaggerated stereo baseline, and the reintroduction of scaling grids.

3.2 TRANSMISSION DEGRADATION

The work statement required a design study of the effects of transmission degradation on vehicle control capability. The effects of noise on a TV image and on the ability to achieve stereopsis are highly subjective. Therefore, analysis of these effects would not yield results in which high confidence could be placed. For that reason the following experiment was devised and conducted.

3.2.1 Summary of Objectives and Results

The general purpose of the experiment was to investigate the effect of various noise levels upon the ability of an observer to make size, distance, and inclination judgements of unfamiliar objects in the stereo model. From these experimental data, a design point for minimum postdetection signal to noise ratio (S/N) can be selected.

The experimental results indicate that an S/N of 22 db gives results that are not significantly worse than those achieved with essentially noise-free pictures. An S/N of 16 db gives significantly worse results, particularly in inclination estimates. Therefore, it can be concluded for the present that 22 db is an acceptable system design point while 16 db is not. A more extensive investigation of signal-to-noise ratios between these two values is suggested.

3.2.2 Experimental Procedure

To obtain the best correlation of experimental data with data obtained from noise-free pictures, the experiment procedure was made identical to that of the main experiment described in Section 3.1.5. However, in view of the time and difficulty involved in setting up and measuring the terrain samples, obtaining pictures, mounting and marking the stereograms, and testing the subjects, it was decided to restrict the experiment to two values of signal to noise. To select properly these two values, a preliminary experiment was designed to measure the range of threshold of stereopsis as a function of signal-to-noise ratio.

3.2.2.1 Threshold of Stereopsis

The threshold of stereopsis phase of the experiment determined the ability of observers to achieve stereopsis as a function of the noise level of a television image. These results established a useful lower limit of image-signal-to-noise ratio and allowed a rational selection of two values of signal-to-noise ratio for the second phase of the experiment.

Observation of images at higher noise levels indicated that detection of stereopsis is a very subjective judgement and cannot be reliably measured by an observer's opinion. Therefore, a more objective measure of stereopsis was devised based upon the observer's performance of a task requiring stereo perception.

In a scene of random rough terrain (see Figure 3-15), three points were identified by means of white markings. A white floating mark was suspended either slightly behind or in front of one of the identified points. The observer was then asked to judge relative position of the floating mark, in front of or behind the referenced point. The scene was presented to the observers by means of the color anaglyph stereo television which is described in Section 2.3.4. This equipment was used to avoid the necessity of mounting and marking a large number of photographic stereograms. For each subject, the test proceeded from the lowest noise images at 34 db to 28, 22, 16, and 13 db, to the highest noise level, 10 db. At each noise level, each subject was asked for six judgements. The sequence of requested judgements was random, but the same for each subject.

A block diagram of the equipment setup is shown in Figure 3-16. Since the scene did not change throughout the test, it was necessary only to adjust the red or blue contrast to give the same peak-to-peak video signal, 42 volts at the start of each test session. This voltage was monitored with a Tectronics 545A oscilloscope. The noise source was a General Radio model 1390A random noise generator. The noise voltage gain of each channel was adjusted to be exactly 100. The RMS voltage outputs of the noise generators were monitored with Hewlitt-Packard 400H VTVM's.

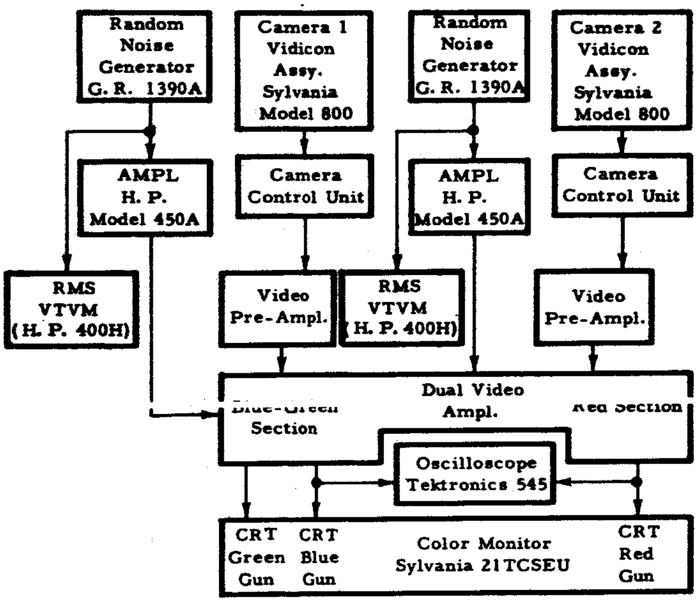
3.2.2.2 Surface Assessment

Because of adverse weather, the camera station for the surface assessment experiment was set up on the lunar terrain model at Willow Run Airport. As in the main experiment, the Kintel model 2020 television camera mounted on a stereo baseline fixture was used to obtain the stereo television images. These were presented on a Kintel model GRM-17 television monitor and photographed on a size 120 roll film by means of a twin lens reflex camera. The resulting photographs were mounted in pairs to form

Figure 3-15 Test Scene for Threshold of Stereopsis

Figure 3-16

THRESHOLD OF STEREOPSIS TEST SETUP



3615-8

stereograms. Camera baselines of 3 and 10 inches, and camera heights of 37-1/4 and 47-1/4 inches were used. In all cases the camera roll angle was zero degrees, the camera was depressed 30° in tilt, camera convergence was zero degrees, and lens focal length was 1/2 inch. The noise source was the General Radio model 1390A random noise generator whose output was amplified and mixed into the composite video output of the television camera (see Figure 3-17). The peak-to-peak video level was adjusted and monitored by means of a Tectronics 545A oscilloscope. The RMS noise level was adjusted and monitored by means of a Hewlitt-Packard 400H VTVM. The peak-to-peak video output from the television camera was 1.7 volts. Therefore, an RMS noise level of 0.27 volts was used to achieve a 16 db S/N, and RMS noise level of 0.135 volts was used to achieve a 22 db S/N. The scene was illuminated with an incidence angle of approximately 27° above the horizon.

Figures 3-18, 3-19, and 3-20 show samples of the photographs obtained with no noise added, 22 db S/N and 16 db S/N.

The eight subjects on the main experiment who had been tested with true stereo pictures were used as test subjects. The subjects were divided into two groups of four which were as nearly as possible balanced in performance on the main experiment tests. Each subject was tested under the same conditions (camera baseline, camera height, and grid overlay) as he had used in the main experiment. One group was shown 16-db pictures, the other group was shown 22-db pictures. For each judgement, a pair of marked points was indicated to the subject and he was asked to judge the distance between the points, inclination of the line joining the two points, and distance from the observer to the midpoint of the line joining the two points.

3.2.3 Tabulated Results

3.2.3.1 Threshold of Stereopsis

Table 3-19 lists the total errors for each observer and total errors at each noise level. These data, converted to error rate, are plotted in Figure 3-21 as the mean, maximum, and minimum error rate.

The mean error rate curve shows an improvement from 34 to 22 db. This effect may be caused by the testing procedure which in all cases started at 34 db and proceeded down to 10 db. Therefore, some learning on the part of the subjects may well have occurred between 34 and 22 db.

Figure 3-17

DATA COLLECTION SETUP: SURFACE ASSESSMENT IN PRESENCE OF NOISE

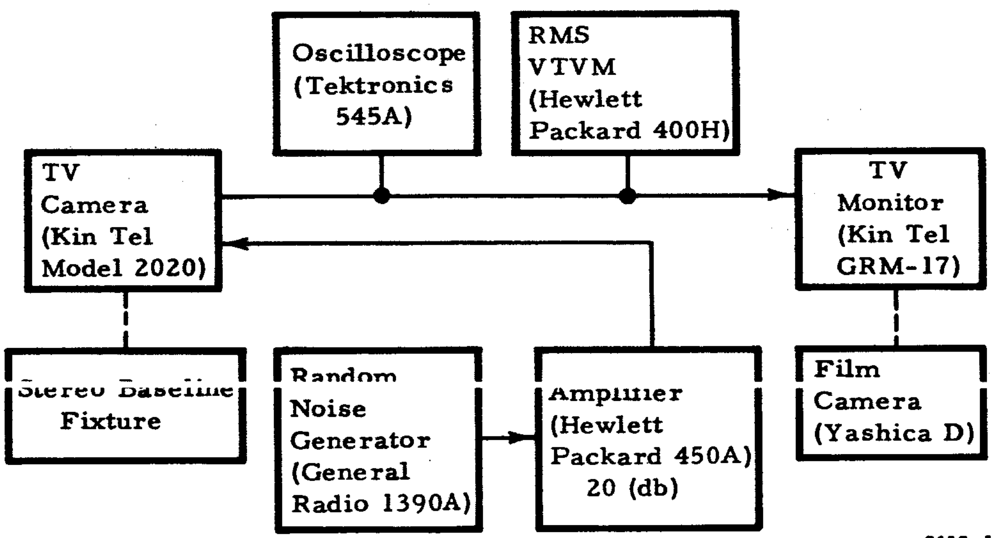


Figure 3-18 Transmission Degradation—Noise-Free

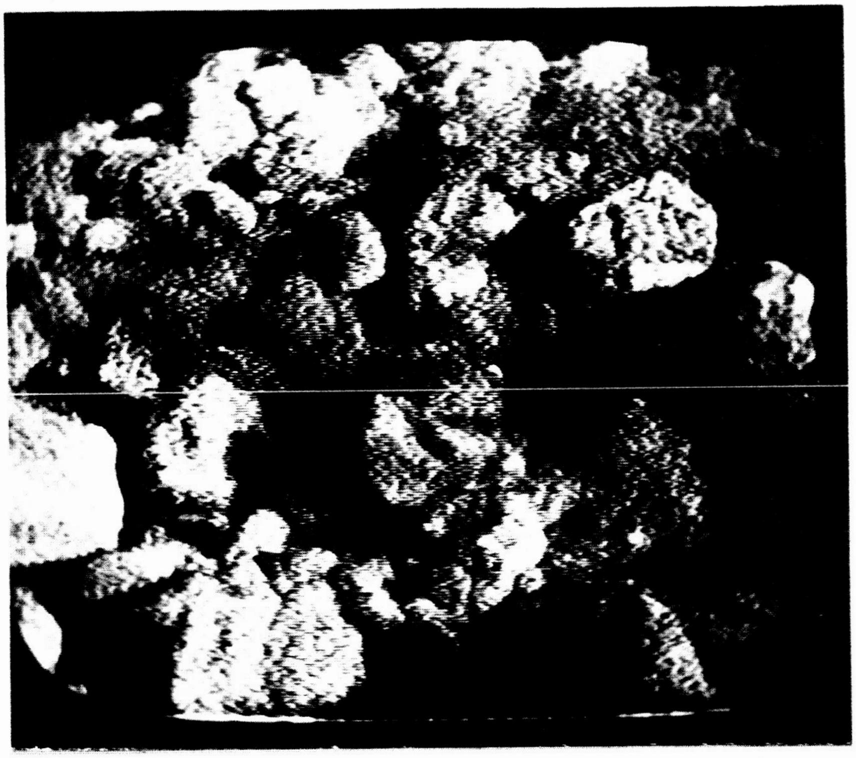


Figure 3-19 Transmission Degradation - S/N 22 db

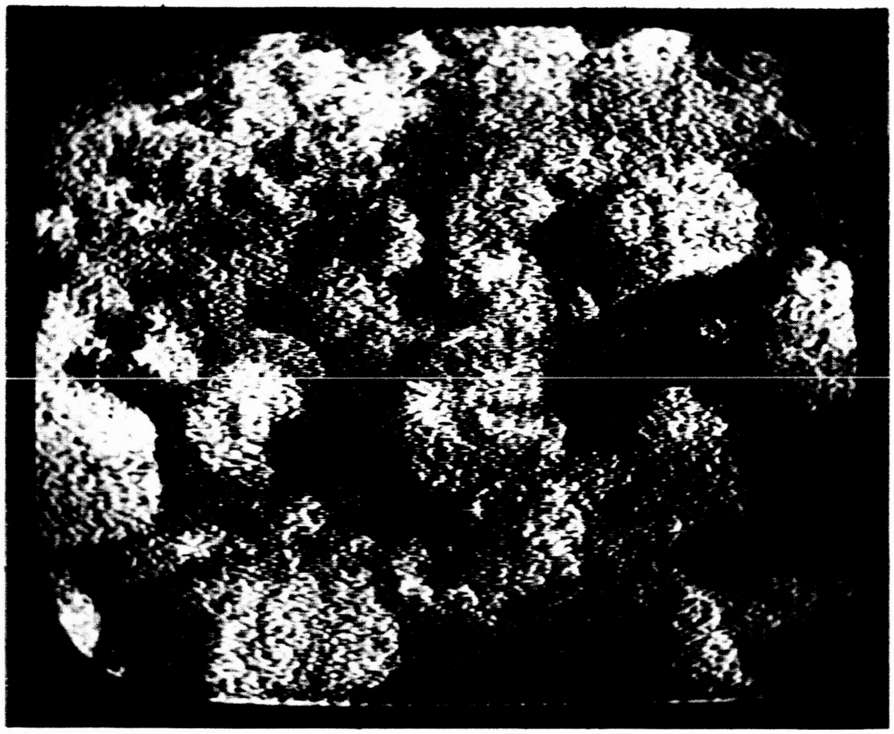


Figure 3-20 Transmission Degradation - S/N 16 db

Figure 3-21

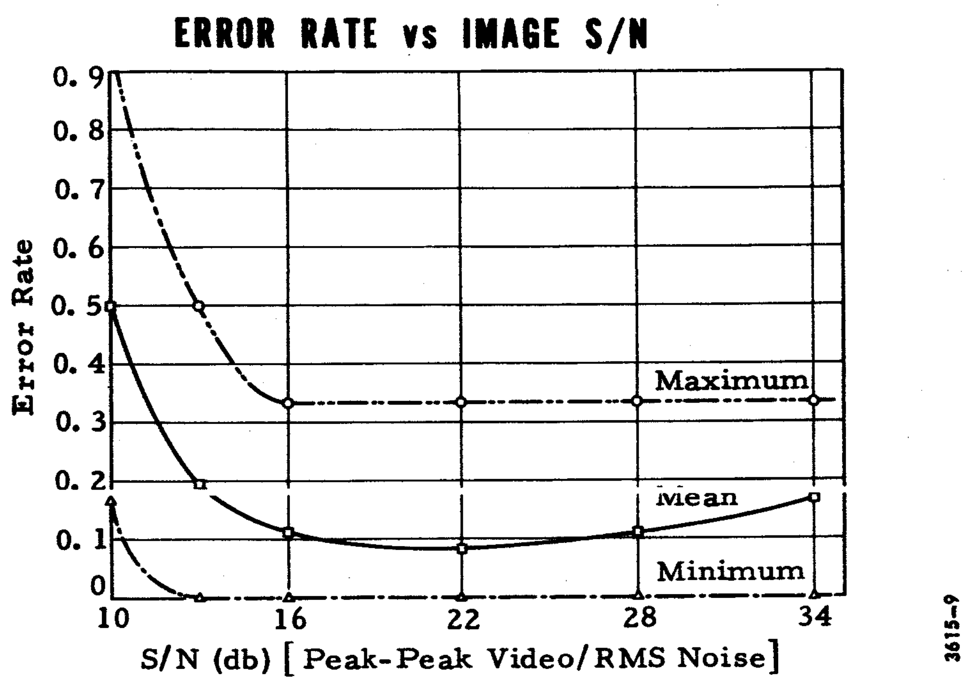

ERROR RATE vs IMAGE S/N
0. 9
0. 8
0. 7
0. 6
0. 5
0. 4
0. 3
0. 2
0. 1
0
Error Rate
Maximum
Mean
Minimum
10
16
22
28
34
S/N (db) [Peak-Peak Video/RMS Noise]
3615-9

TABLE 3-19

SUBJECT ERRORS ON THRESHOLD OF STEREOPSIS TEST

S/N (db)	Subject						Total Error
	1	2	3	4	5	6	
34	2	1	2	0	1	0	6
28	2	0	1	0	1	0	4
22	2	0	0	0	1	0	3
16	2	0	0	1	1	0	4
13	3	0	0	0	1	1	7
10	3	2	2	3	6	3	18

Aside from the numerical data, all six subjects reported no reliable stereopsis at 10 db. One of the subjects reported no reliable stereopsis at 13 db.

There appears to be considerable variance in the test results, however the data curve displays a definite knee starting at about 16 db, which should establish a useful lower limit for stereopsis. It was therefore decided that the second phase of the experiment would use 16 and 22 db as noise parameter values.

3.2.3.2 Surface Assessment

Each test subject was asked to make 20 judgements each of distance-between, inclination, and distance-to-midpoint. From the tabulated responses, raw error was determined and the mean, variance, and standard deviation were computed. Because of the relatively small volume of data, no attempt was made to partition the results other than by noise level. This yielded 80 samples of each judgement type at each noise level. Partitioning by such variables as baseline, camera height, or scaling aid would have yielded sample totals of 40 or less for each variable condition. An attempt was made to determine the extent of subject learning of the scene during the course of the test. This was accomplished by computing the standard deviation of both the first 10 and the second 10 judgements of each subject for each judgement type. Most subjects displayed a considerable variation in performance between the first and second half. However, both positive and negative learning appeared in approximately equal amounts in all three judgements types. Therefore, it was assumed that the effects of subject learning of the scene were not of great significance in this experiment.

Table 3-20 presents the tabular results of the two subject groups on the distance-between judgements. For comparison, the table also presents the performance of the same subjects on this judgement during the main experiment on essentially noise-free pictures. Table 3-21 presents the identical data for the inclination judgement and Table 3-22 for the distance-to-midpoint judgement. The results show the standard deviation of inclination to be the most sensitive to variation of signal to noise ratio. Figure 3-22 shows a very distinct knee occurring at about 22 db. Above this value of S/N, little improvement in the standard deviation is noted. The summary data from the main experiment are plotted as a value of 34 db. In fact, at the time the data for the main experiment were collected, the S/N of the video signal was not recorded. However, it was noted during the threshold of stereopsis phase of this experiment that at a 34 db S/N the presence of noise on the television image was only barely discernible to most observers. Therefore, 34 db was arbitrarily used as the assigned value for those pictures from the main experiment which had no noise artificially added.

As shown in Figure 3-23, the standard deviation of distance-between estimates, while increasing as the S/N is decreased, do not display the same sensitivity to S/N as the inclination estimates. While there are not sufficient data points to support this, the curve has been drawn asymptotic to 10.6 inches at 34 db because no significant improvement of performance above 34 db could realistically be expected.

The standard deviation of distance-to estimates displays very little sensitivity to S/N. In Figure 3-24, two values of sigma have been plotted at 34 db: that for the total main experiment and that for the second half only. These show that considerable learning on this particular task occurred during the main experiment. It therefore seems most valid to compare performance on the second half of the main experiment with the

TABLE 3-20

SUBJECT PERFORMANCE, DISTANCE-BETWEEN

Subject	S/N	Transmission Degradation		Main Experiment (Noise-Free)	
		Mean Error (inches)	Standard Deviation (inches)	Mean Error (inches)	Standard Deviation (inches)
1	22	+3.7	11.5	+3.4	9.6
2	22	+3.9	8.7	+2.5	8.5
3	22	-4.4	13.8	+1.1	8.5
4	22	+3.9	17.6	+1.9	10.8
22 db group		+1.3	13.9	+2.0	9.5
5	16	-3.8	17.8	+5.8	13.4
6	16	-9.7	13.1	+0.8	8.7
7	16	-5.9	13.0	+7.8	13.6
8	16	-9.0	11.9	-2.9	6.7
16 db group		-7.1	15.6	+2.9	11.8

TABLE 3-21

SUBJECT PERFORMANCE, INCLINATION

Subject	S/N	Transmission Degradation		Main Experiment	
		Mean Error (inches)	Standard Deviation (inches)	Mean Error (inches)	Standard Deviation (inches)
1	22	+10.9	13.2	+1.0	16.0
2	22	+12.7	22.8	+4.3	13.3
3	22	+10.2	16.6	+5.8	16.1
4	22	+ 7.3	21.0	-0.8	27.0
22 db group		+ 8.9	19.6	+2.5	19.3
5	16	- 7.2	26.0	+3.1	17.2
6	16	+ 2.7	18.4	+3.3	15.2
7	16	+ 9.0	31.6	-0.9	22.0
8	16	- 4.2	17.7	+2.9	20.2
16 db group		+ 1.5	24.9	+2.1	18.9

TABLE 3-22

SUBJECT PERFORMANCE, DISTANCE-TO-MIDPOINT

Subject	S/N	Transmission Degradation		Main Experiment	
		Mean Error (inches)	Standard Deviation (inches)	Mean Error (inches)	Standard Deviation (inches)
1	22	- 9.9	18.1	-1.0	29.6
2	22	- 9.6	17.1	+3.7	16.0
3	22	- 6.5	14.8	-7.7	20.8
4	22	-23.1	17.6	-7.5	18.9
22 db group		-12.3	18.1	-3.1	22.4
5	16	-13.6	22.9	-15.5	32.7
6	16	-13.4	24.5	-1.8	21.9
7	16	-37.5	13.7	-9.4	20.2
8	16	-15.6	10.8	-0.7	14.4
16 db group		-19.9	21.6	-6.9	24.0

Figure 3-22

STANDARD DEVIATION OF INCLINATION AS A FUNCTION OF S/N

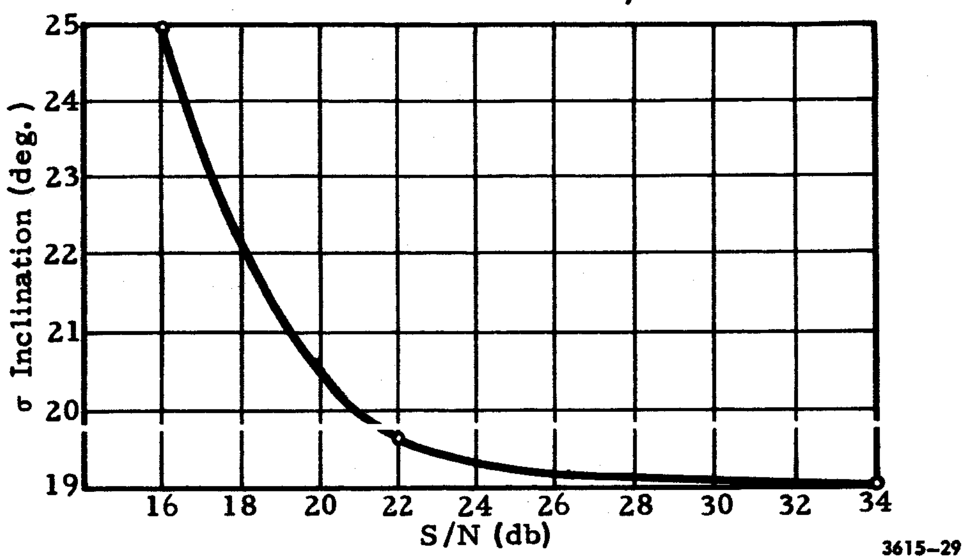
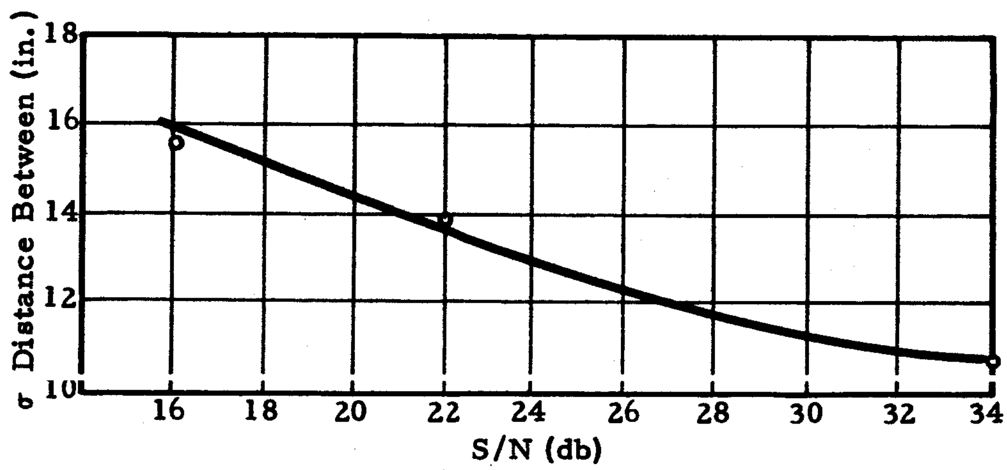


Figure 3-23

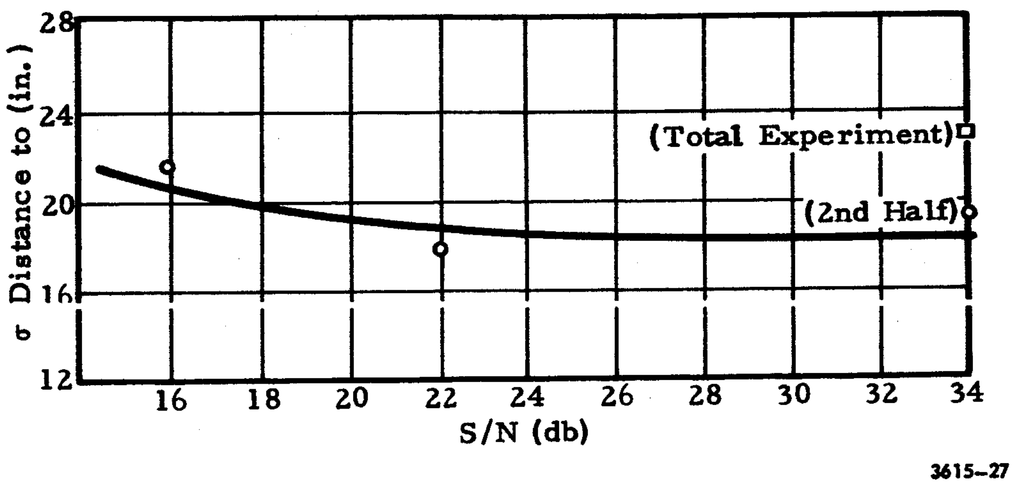
STANDARD DEVIATION OF DISTANCE BETWEEN AS A FUNCTION OF S/N



3615-28

Figure 3-24

STANDARD DEVIATION OF DISTANCE TO
AS A FUNCTION OF S/N



results under noise conditions. While the standard deviation of distance-to estimates was not sensitive to S/N, the mean value of distance-to errors displayed a high sensitivity to S/N, as shown in Figure 3-25. No explanation for this result is apparent.

At the end of each test session the comments of each subject concerning the image quality and his willingness to attempt driving the vehicle with images of this quality were solicited. The following are the general sense of those comments.

> Subject No. 1, 22db: "Quality OK for driving, fusion not solid, bothered my eyes."
>
> Subject No. 2, 22-db: "Noise obscures the surface texture which helps define planes. Sufficient information for the driving."
>
> Subject No. 3, 22 db: "Noise not distracting."
>
> Subject No. 4, 22 db: "Quality no worse than no-noise pictures."
>
> Subject No. 5, 16 db: "Had general impression of topography. Could drive vehicle with greater safety factors."
>
> Subject No. 6, 16 db: "Stereo poor, decisions based on experience more than stereo model."
>
> Subject No. 7, 16 db: "Would make decision on picture of this quality."
>
> Subject No. 8, 16 db: "Difficult to judge line orientation. Not good enough to drive with."

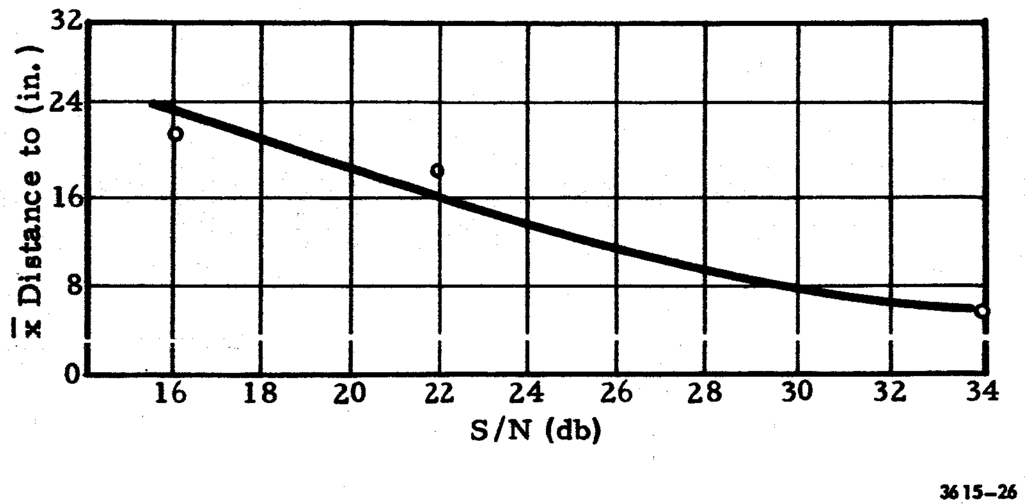
3.2.4 Conclusions and Recommendations

By the measure of standard deviation, only in the distance-between judgements was there any significant decrease in performance from 34 to 22 db. In both the inclination estimates and the distance-to estimates, there was no significant difference between performance at 34 and 22 db.

It can be argued that in making estimates of distance-to, subjects tend not to use the cues available in the stereo model but rely more on synoptic cues. This might explain why performance on distance-to estimates did not become worse with deterioration of the stereo model.

Figure 3-25

MEAN ERROR OF DISTANCE TO AS A FUNCTION OF S/N



Regarding the subjective opinions on image quality, all four subjects at 22 db apparently felt the image quality was less than optimum but was still sufficient. For the subjects at 16 db, only two appeared to indicate sufficient confidence in their judgements for driving purposes. Significantly, the two subjects who felt the images were of sufficient quality had among the highest standard deviations of all subjects tested.

It can be concluded that images with S/N of 22 db appeared to have sufficient quality for vehicle driving. Images with a 16 db S/N do not appear to be of sufficient quality for driving.

Future investigations in the effects of transmission degradation should be concentrated in the area between 22 and 16 db. It may well be possible that performance at S/N values less than 22 db but greater than 16 db are still acceptable or may be very useful for a degraded mode of operation.

Any further investigation should also aim to collect a significantly larger volume of data so that the results can be partitioned by variables such as range, inclination, length, or location in the scene. This information would give much greater insight into precisely how the stereo model is degraded by the effects of noise.

If possible, future investigations should attempt to use subjects of uniform and high stereoptic acuity. This would help to reduce the considerable variance in performance between subjects.

3.3 SURFACE LIGHTING

An experiment was performed to evaluate the effect of surface lighting angle and gray level coding on the remote control task. Specifically, two questions were investigated:

1. How does the solar incidence angle affect surface picture quality?

2. Should TV picture gray level coding be varied as a function of sun angle, and if so, how?

For the tests, two surface models were illuminated from various selected lighting angles. The models were viewed with a conventional closed-circuit TV system. Black and white stereo pair photographs were made of the monitor for each test case. The resultant photographs were evaluated and results are described later in this report.

The test setup is shown in Figure 3-26. The surface models, composed of foundry slag, were constructed on a 4 x 4 ft platform. The model was illuminated by a 1000-watt quartz iodide lamp located at the focal point of a 24-inch paraboloidal reflector. This arrangement provided a high intensity, well collimated light source. The beam spread was approximately 1.5°, providing a 27-inch spot of 3000 lumens per square foot at a distance of 10 ft. A plane mirror arrangement was used to allow for easy direction of the lamp illumination on the model. Thus, simply by changing the mirror angle and locating the mirror properly, any desired lighting angle on the model could be achieved. During tests, the room was dark except for the 24-inch lamp. The model in use was shielded from direct filament illumination and, as well as possible, from ambient reflected illumination, being lighted only by the collimated beam off the mirror. The models were viewed by a KinTel closed-circuit TV system. A 1/2-inch focal length lens was used, providing a 53° horizontal field of view and a camera depression angle of 30°. A parallax bar mechanism was mounted on the camera tripod to allow stereo baseline and convergence angle adjustments. Experimentation showed that a 2 inch stereo baseline with zero convergence provided the best compromise between ease of viewing and stereo acuity. (The TV camera was approximately 2 to 4 ft from the surface model.) The resultant pictures displayed on the TV monitor were photographed for subsequent stereo mounting.

Special attention was given to the selection of suitable surface models. First, consideration was given to the use of Photomat. This surface model, developed by Bendix, closely simulates the observed photometric properties of the lunar maria. The desire for a random surface, however, led to the selection of foundry slag. Although slag does not match the lunar photometric function as well as Photomat at large phase angles, its irregular shapes allow a random surface profile to be constructed easily. Two slag surface models were constructed. The first, designated the hard model, was composed of hand-selected pieces in a 1 to 4 inch size range. The second model, designated the soft model, was composed of similar slag crushed into pieces of 1/2 inch and smaller. For both models, the slag was placed on a 4 x 4 ft piece of plywood which had been covered with Photomat to provide a dull, nonreflecting background. The normal reflectance of the two models was determined to be 0.068 and 0.087 for the hard and soft models, respectively. The soft model can be seen in the photograph of Figure 3-26, on the table and reflected in the mirror.

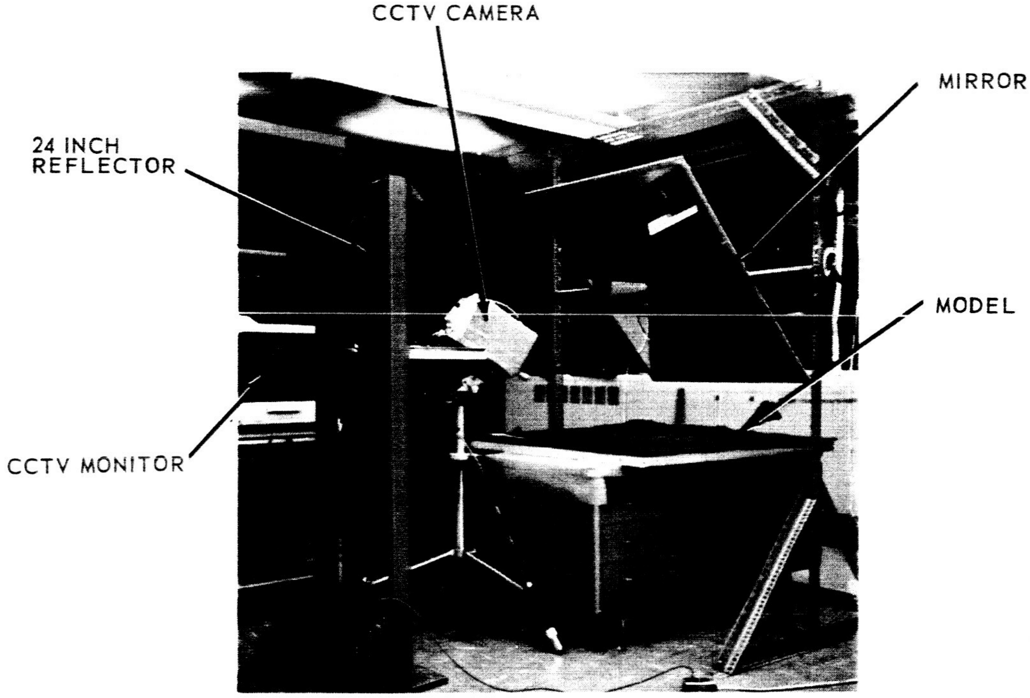


Figure 3-26 Experiment Setup

The approach to studying various gray level codings was to use a conventional analog TV system, effectively varying the total number of gray levels by varying the contrast between levels. This is equivalent to changing the slope of the system transfer characteristics. A RETMA chart gray scale was used as a standard. Three gray level coding conditions were studied: (1) L_1 presents pictures with an even gray level coding. (2) L_2 expands the contrast between the dark levels and saturates the light end. For condition L_2, only six gray levels were used; gray wedges 1 through 5 on the RETMA chart therefore appear as white, with wedges 6 through 10 being discernable. The contrast between levels is therefore 5 db instead of the nominal 3 db. (3) L_3 is the complement of L_2; again, six gray levels are used (approximately 5 db separation) coded in the light end of the spectrum. Gray wedges 6 through 10 on the RETMA chart all appear black for condition L_3.

In selecting lighting angles, a compromise had to be reached between the number of conditions studied and experiment size. The lighting angle is defined in terms of two angles, ϕ_1 and ϕ_2, measured with respect to the local vertical.

ϕ_1 : Measured in plane of camera and local vertical; positive angle represents back-lighted condition

ϕ_2 : Zenith angle normal to ϕ_1; no sign convention required.

Thus, a sun angle of $\phi_1 = \phi_2 = 0^\circ$ represents the sun directly overhead. A sun angle of $\phi_1 = 0^\circ$, $\phi_2 = 45^\circ$ represents a side-lighted condition at a 45° angle. A sun angle of $\phi_1 = 45^\circ$, $\phi_2 = 0^\circ$ represents a front-lighted condition with the sun directly ahead of the camera at an angle of 45° from the vertical. When $\phi_2 = 90^\circ$, the sun is at the horizon. The above definitions then are modified as follows. For this case, ϕ_1 becomes the solar azimuth angle, with the value $\phi_1 = 0^\circ$ being the side-lighted case. Then, following the previous convention, a positive value of ϕ_1 represents a back-lighted condition. Thus, a sun angle of $\phi_1 = -30^\circ$, $\phi_2 = 90^\circ$ represents the sun at the horizon, front-lighting the camera at an angle of 60° from the camera line of sight.

Table 3-23 lists the conditions studied. The 49 test points were selected to provide a reasonable coverage of the cases of interest without excessively burdening the test procedure.

TABLE 3-23

EXPERIMENT TEST CONDITIONS

Soft Model				Hard Model		
$\phi_2 = 0^\circ$						
ϕ_1	L_1	L_2	L_3	L_1	L_2	L_3
-75	X	X	X	X	X	X
-45	X					
0	X	X	X	X	X	X
45	X					
75	X	X	X	X	X	X
$\phi_2 = 45^\circ$						
-75	X	X	X	X	X	
-45	X					
0	X	X		X	X	
45	X					
75	X	X	X	X	X	
$\phi_2 = 90^\circ$						
-60	X	X	X	X		
-30	X					
0	X	X	X	X		
45	X	X	X	X		

The procedure for each test was identical. The mirror was set to the appropriate angle for the lighting angle under consideration. The model-mirror separation was then adjusted to provide the best coverage of the model and the TV camera located at the proper viewing position. After shielding the model from external lighting, the gray scale reference was placed on the model. The lens f-stop and monitor brightness and contrast were adjusted until the desired gray level rendition was achieved. A stereo picture pair of the monitor was made with a Yashica reflex camera, moving the TV camera 2 inches between pictures. The following data were recorded for each condition: ϕ_1, ϕ_2, gray level condition, TV camera f-stop lamp mirror-model distance, and TV camera-model distance. The resultant photographs were printed on a matte paper and mounted as stereo pairs for stereoscope evaluation.

Two approaches to picture evaluation were considered. The first, using microdensitometer measurements and subsequent analysis, was felt to be beyond the scope of the study program. The second approach utilized a subjective evaluation of the surface model pictures to determine picture quality as a function of lighting angle and gray level coding. A parallel procedure would establish what picture quality, graded on the same scale, is necessary for driving the vehicle. Then, by cross-plotting the two, the merits of the three gray level codings can be evaluated at various lighting angles. Fifteen test subjects were selected on the basis of stereo perception and familiarity with the remote control task. Each subject evaluated the stereograms on the following basis:

1. Scene brightness (overall lighted scene brightness)

2. Picture contrast (ratio of brightest to darkest areas in picture)

3. Picture detail (large-scale and small-scale features)

4. Overall picture quality (defined in terms of the above).

These parameters were graded on a scale of 1-2-3-4, with the value 1 being the poorest ranking for each category. In addition, each subject was asked:

> "Disregarding scale, does this picture present enough information to allow formulation of a decision to drive or not to drive the vehicle?"

By asking each subject to rank each picture, nearly 750 data points on picture quality evaluation and necessary picture quality were obtained.

Following the evaluation procedure, analysis of the data was initiated. The mean value of each picture parameter was used for all plots. Parameter means were obtained by averaging the ratings for each parameter for each picture over the 15 subjects. The primary description of picture quality was selected as Overall Picture Quality (OPQ). This parameter reflects the subject's evaluation of the picture in terms of brightness, contrast, and detail. It was first felt that OPQ was related to the product of the three. However, a scatter diagram showed no particularly strong correlation. Thus, a possible correlation between OPQ and each of the three contributing parameters was investigated. The results indicate little correlation of OPQ with brightness, mild correlation with picture contrast, and a strong correlation with picture detail (see Figure 3-27). Therefore, picture detail was the parameter of most concern to the subjects. This was evident during the testing. Even though a picture may have been dark or of low contrast, if detail was not lost the picture generally received a good rating. The concern with detail raised another question. As picture brightness and contrast are increased, picture detail is increased but eventually decreases. This results from the saturation of the light areas of the picture with corresponding loss of detail. Therefore, OPQ should exhibit an optimum when plotted against brightness-contrast product. This plot was constructed from the test results. The data were not conclusive, although a slight tendency toward an optimum was detected.

Figure 3-28 illustrates the picture rejection probability as a function of OPQ. The three data points lying above the straight-line curve result primarily from the high picture rejection rates for the sun on the horizon. The large deep shadows constituted too much uncertainty for most subjects. This curve presents the required picture quality to achieve a desired picture acceptance probability. . Rejected pictures represent a direct waste of time, since another picture must be called for, generally for the same area. Therefore, a low rejection probability is desired. After establishing a permissible rejection probability, the required picture quality is determined. It then becomes necessary only to assure that a picture of that quality is provided.

Coding condition L_1 generally presents a dark picture with heavy shadows. This is particularly true for adverse lighting conditions, when the scene is front-lighted. Comparison of the L_1 and L_2 coding conditions

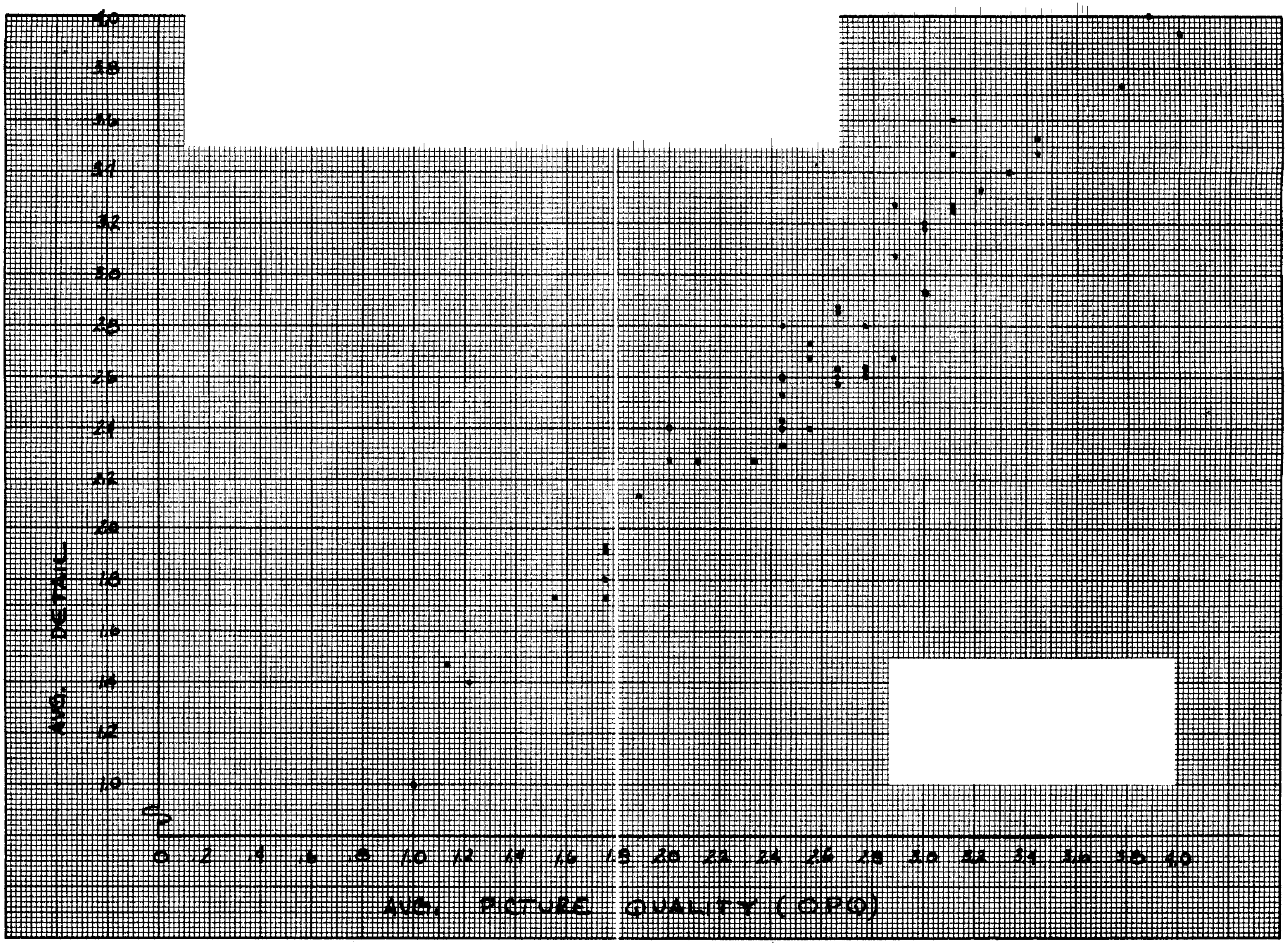


Figure 3-27 Scatter Diagram–Picture Detail Vs Picture Quality

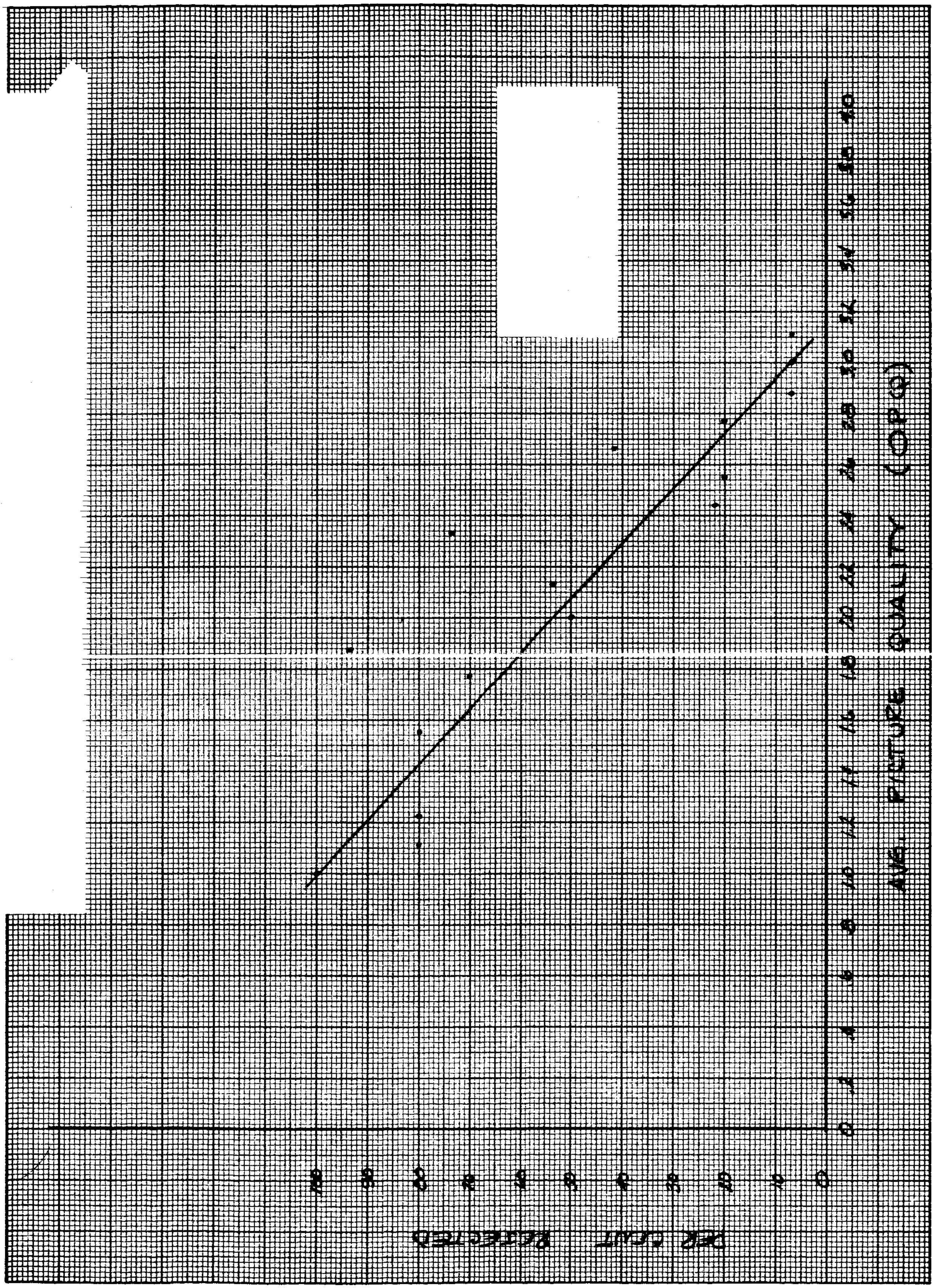


Figure 3-28 Picture Rejection Vs Picture Quality

indicates that L_2 pictures generally are superior to L_1 pictures, particularly at adverse lighting conditions. Condition L_2, in expanding the dark end of the scale, provides much greater detail in dark and shadowed areas, at the expense of saturated highlights. The net result is a significant improvement in picture quality. Condition L_3 produced very dark pictures of good detail but with large undefined areas. Condition L_3 therefore generally produced pictures inferior to L_1 or L_2, as expected.

Figures 3-29, 3-30, and 3-31 present the results of the picture evaluations. The results for the soft model were less meaningful than those for the hard model. The following comments can be made:

1. The soft model did not present the numerous deep shadows of the hard model and therefore generally received a somewhat better rating for identical conditions.

2. There does not appear to be any substantial difference in picture quality for the soft model for the three gray level coding conditions.

3. The choice of the primary surface model was unfortunate. The intermediate data points would have been of more value for the hard model. Results for the hard model appear to be more consistent. Condition L_2 provides better pictures at adverse lighting conditions than does L_1; condition L_3 is poorest of all. As the sun moves overhead and behind the camera, there is less of a difference between L_1 and L_2.

The general form of the results, particularly for the soft model, was not as expected. For any given gray level condition, it was expected that picture quality would generally follow the photometric function, peaking at zero phase angle. Several factors might explain the discrepancy. First, the test procedure relied upon experimenter judgement to maintain tonal composition constant for each gray level condition. The alternative, which was considered and rejected as excessively time consuming, was to check each setting with Polaroid prints until a consistent picture was obtained before taking the actual stereo photographs. Although each test subject was found to be rather consistent in his picture evaluations, as determined by cross-checks, variations did exist between subjects. These variations may contribute to the discrepancy. The most likely explanation, however, is the physical structure of the models. The soft model was plain and featureless except for several gentle depressions. Thus, even at adverse

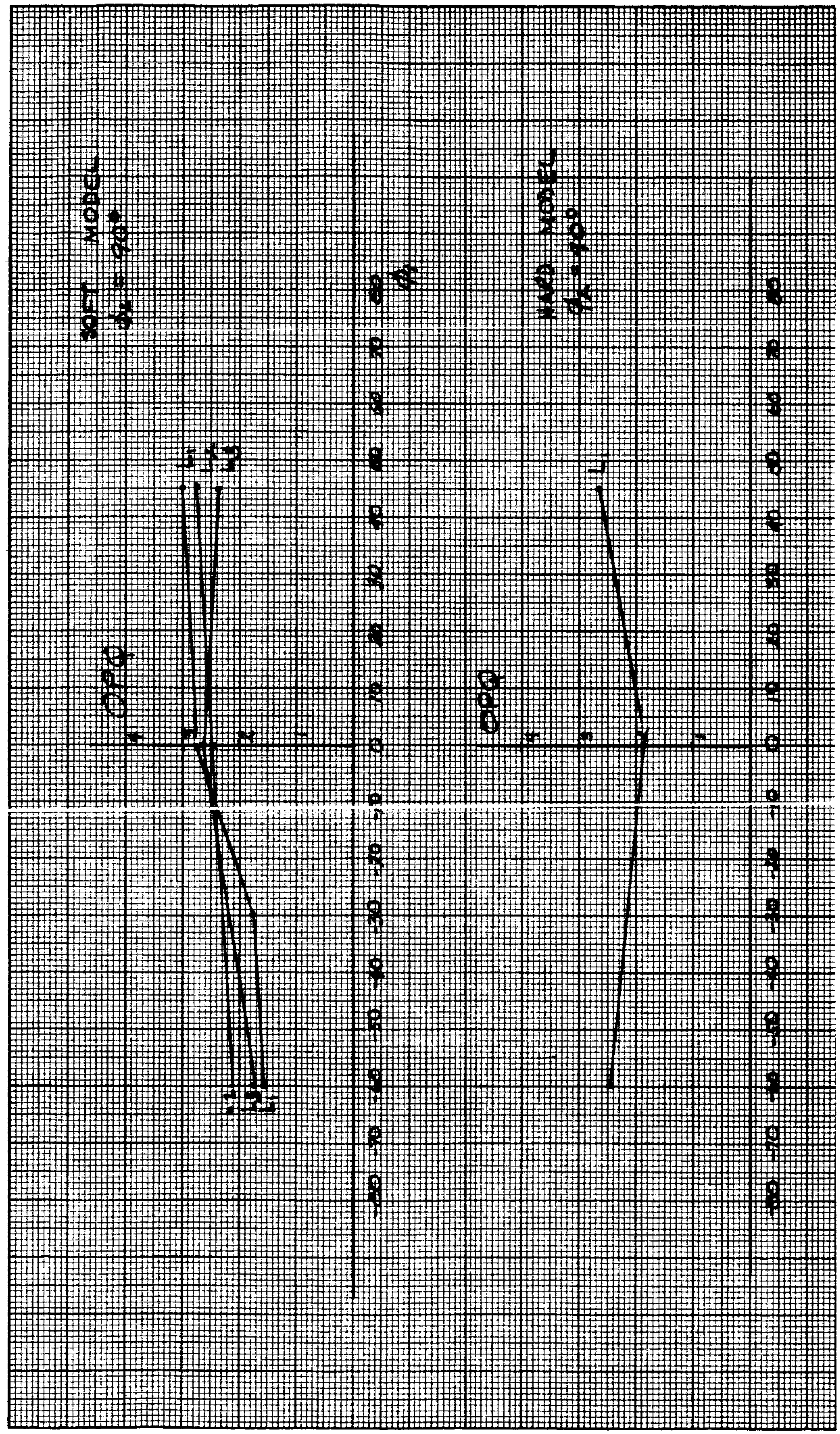


Figure 3-29 Picture Evaluation Results, $\phi_2 = 90^{\circ}$

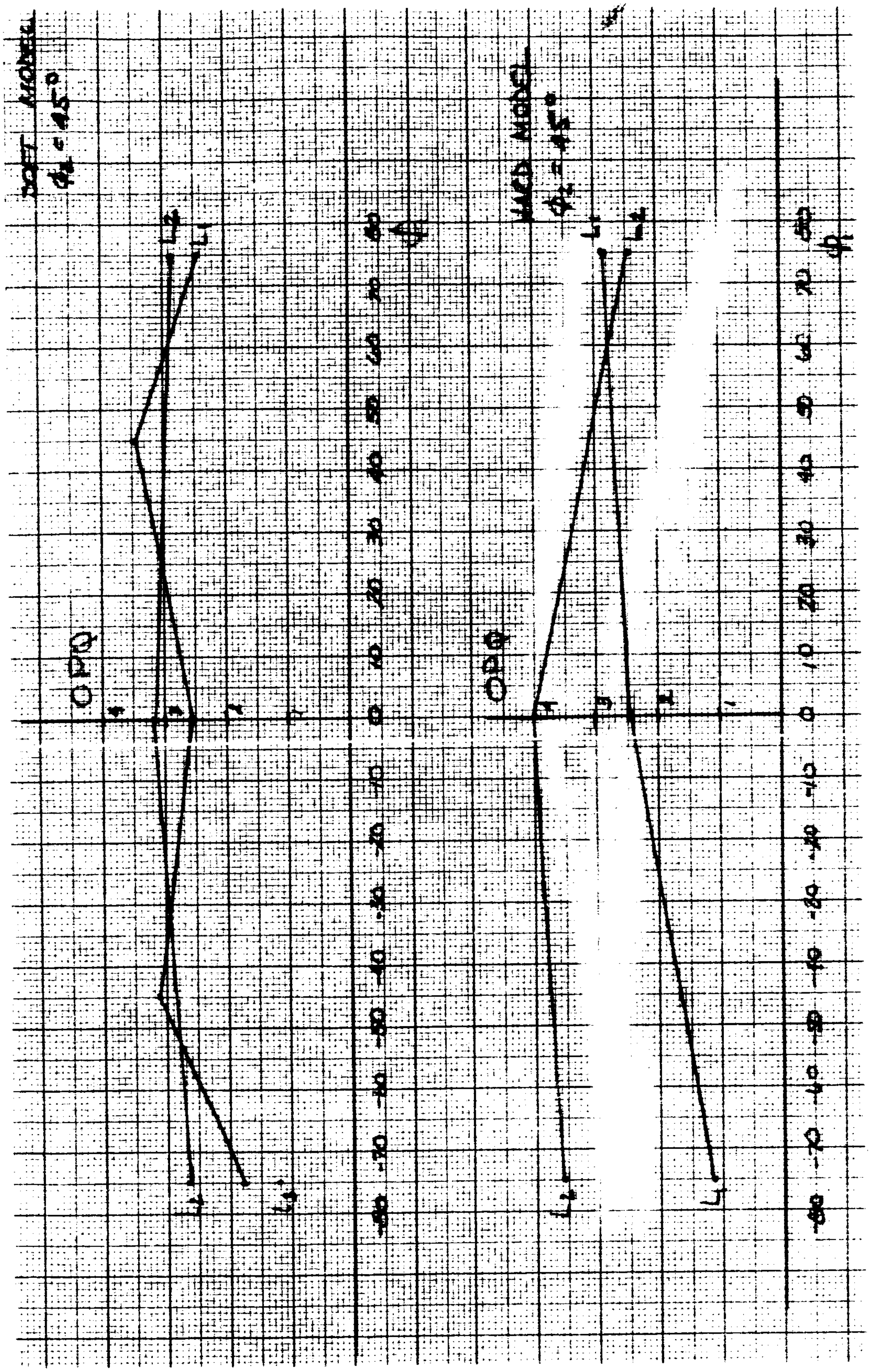


Figure 3-30 Picture Evaluation Results, $\phi_2 = 45^{\circ}$

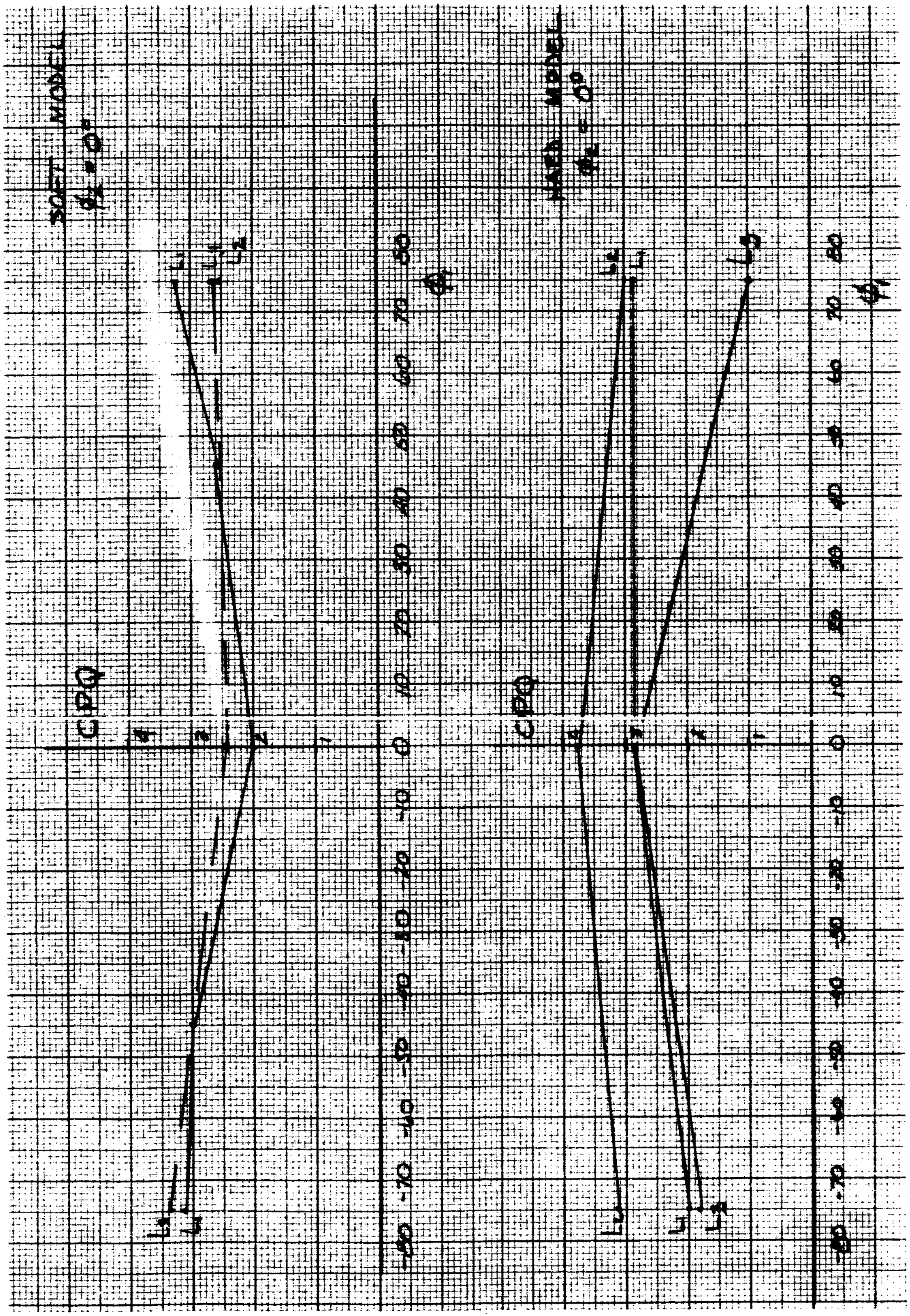


Figure 3-31 Picture Evaluation Results, $\phi_2 = 0^\circ$

light angles, the scene is fairly evenly lighted. The low light level can be accounted for by adjusting the TV camera lens aperture, providing dynamic range and depth of field are not restrictive. The hard model should exhibit more sensitivity to lighting angle. This was observed, but not conclusively.

Test results are summarized as follows:

1. A method of rating picture parameters for various lighting angles and gray level codings was established, allowing determination of the required picture quality for various conditions.

2. Picture detail is the primary contributor to overall picture quality.

3. Picture detail in dark or shadowed areas can be increased by expanding the contrast in the dark end of the picture, even though picture highlights are driven into saturation. A noticeable improvement is provided for rocky random surfaces, particularly at adverse lighting angles.

4. For smooth featureless surfaces, picture quality is not expected to vary significantly with lighting angle, as long as the TV cameras have sufficient dynamic range and depth of field. Expanded gray level coding does not appear to be necessary.

3.4 PATH PREDICTION

3.4.1 Introduction

This section describes a computer simulation conducted to investigate the advantages of ground prediction of the vehicle's anticipated position resulting from control commands.

The SLRV Phase I study investigated various modes of vehicle control. One constraint revealed by the Phase I study was that the vehicle must operate in a discontinuous manner. Other efforts on remote control during Phase I were concerned with evaluating possible modes of operation within the overall concept of discontinuous driving. The control concept recommended in Phase I was a real-time-command, closed-loop control system employing a computer-generated predicted vehicle path superimposed upon the TV image. The purpose of path prediction was to compensate for the effects of time delay in the control loop and relate the vehicle's steering dynamics to the surface geometry revealed by the TV imagery.

Several degrees of path prediction are possible. The simplest is present position prediction in which the vehicle's last reported position, in lunar time space, is extrapolated to operator time space on the basis of commands already given, but not yet acted upon by the vehicle, and known vehicle steering dynamics. Thus, to the extent that the vehicle's response to commands is predictable, this simplest form of prediction cancels the effects of time delay insofar as control system dynamics are concerned. This form of prediction does not, however, tell the operator where the vehicle will be at some future time, nor does it tell the operator when he should initiate a steering maneuver to achieve some desired path. These latter functions can be accomplished by predicting the vehicle's position at successive increments of future time. Any such future prediction must, of course, make some assumption regarding future commands. The simplest assumption is that the present command state will be maintained. A predicted path based upon this assumption would show the operator where the vehicle would go if the present command state is maintained. This is the form of path prediction which has been evaluated during this study. More sophisticated forms of path prediction are possible but were beyond the scope of this study.

Path prediction has been discussed thus far only in the context of closed-loop control, but it is also applicable to open-loop control. As used here, open loop refers to a method of operation in which the steering commands are formulated completely before the vehicle is set in motion and are unalternable, except perhaps for an emergency stop command, during the step movement. Open-loop control does not require navigation data for control purposes. Closed-loop control does not require the formulation of an entire sequence of commands before the vehicle is set in motion but permits the transmission of the necessary steering commands as they are required to achieve a particular direction of travel or path. Closed control requires navigation data for its implementation. In open-loop control, however, path prediction would be used to assist in planning a sequence of steering maneuvers which would then be given to the vehicle.

Various levels of complexity of path prediction are also possible for open-loop control. The simplest useful form of path prediction for open-loop control consists of predicting the path the vehicle would follow assuming that a single steering state is maintained for the entire step. This is the type evaluated in this study. Next in complexity is prediction of the vehicle path for a finite number of predetermined path sequences. The most sophisticated form of path prediction for open-loop control would provide a separate simulation of vehicle steering dynamics allowing the operator to drive this simulated vehicle in real-time closed-loop fashion, thus generating a unique sequence of commands for the particular step which would be subsequently transmitted to the vehicle for execution in open-loop fashion.

The most appropriate way to represent the vehicle's predicted path on a TV display is believed to be by two lines representing the outside edges of the vehicle's expected track. The ability to predict accurately and display a predicted path in the coordinates of a typical TV profile view of the surface is dependent upon the extent to which the surface gross slope characteristics are considered. If the predicted path is computed assuming a generally flat surface, when in reality there is a large change in slop along that path, the displayed path will have geometric errors in relation to the displayed image of the surface.

3.4.2 General Test Plan

The utility of path prediction on remote vehicle control performance within this study was examined using the Bendix COED (Computer Generated Electronic Display) and a computer simulation of both surface characteristics and vehicle steering dynamics. One of the constraints imposed by the program scope was to design a test program which would minimize both computer time and subject time. Such a test program is shown in Table 3-24. A detailed description of the simulation facility and specific characteristics of the six different experimental conditions is provided in Section 3.4.3. Basically, the last four conditions are the ones of interest. The first two conditions serve as training and standardization runs for the subject group. Since each of the main experimental conditions, conditions 3 through 6, were expected to require different learned behavior on the part of the subject and since the total number of both subject and computer hours were to be minimized, the experimental design provided for only one subject on each of the prime conditions.

3.4.3 Simulation Description

The COED Mark II is a general-purpose device used for man machine communication (see Figure 3-32). The main COED display

Figure 3-32 COED Display Console

TABLE 3-24

PATH PREDICTION EVALUATION TEST PROGRAM

Test Condition	Subjects	Number of Trials
1. Closed-loop control, path prediction, no path perturbations, no time delay	A, B, C, D,	One each
2. Closed-loop control, path prediction, path perturbations, no time delay	A, B, C, D,	One each
3. Open-loop control, no path prediction, path perturbations	A	Two
4. Open-loop control, path prediction, path perturbations	B	Two
5. Closed-loop control, no path prediction, path perturbations, time delay	C	Two
6. Closed-loop control, path prediction, path perturbations, time delay	D	Two

consists of a 19-inch cathode ray tube on which a configuration of lines and symbols can be displayed under computer control.

The SLRV vehicle control simulation program contains two basic elements: a surface simulation, and a vehicle simulation. The simulated surface on which the simulated vehicle is driven was designed to represent an area with randomly distributed hazards. Mathematically, the simulated surface consists of a square area 128 meters on a side with the area divided into cells 1/4 meter on a side. Hazard areas are located in this field randomly in accordance with a hazard probability value assigned by a data card. This value determines the probability of a hazard area being centered in each cell of the field. For this study, the hazard probability was 0.01. A hazard area is represented by a circle of one of three diameters selected in accordance with a second random distribution. Hazard area diameters used in this test were 0.3, 0.7, and 1.5 meters. Thus, the hazard areas are typically larger in size than the cells which determine their existence, and overlapping areas can and do exist. The resulting appearance of the simulated surface, as viewed from overhead, is similar to that of some of the recent Ranger photographs. Although the basic area has finite limits, the simulation program is so designed that it is impossible to run out of surface on which to drive. The basic area is repeated as necessary to provide a limitless surface. Although the location of hazard areas is random, the same identical random area, once produced, can be used over and over again so that specific paths are repeatable from one run to another.

A typical picture as seen from the simulated camera on the vehicle and displayed on the COED screen is shown in Figure 3-33. The maximum detection distance for hazard areas in the simulation is 15 meters. This means that any hazards more than 15 meters away, even though within the field of view, will not appear on the display. To add greater realism to the appearance of the simulated terrain, the camera pointing angles are perturbed by the amount of vehicle pitch and roll at each stopping point. Pitch and roll angles for the vehicle area related to the vehicle's distance and orientation to the nearest hazard area. If the front of the vehicle is pointing directly at a hazard area, pitch-up is induced. If the rear of the vehicle is pointing at the closest hazard area, pitch-down is induced. If the three points defining the vehicle are on a radial line to the nearest hazard area, then only roll is induced.

The simulated vehicle is defined by three points corresponding to the right and left front corners of the vehicle and a point midway between these two, defined as the center of gravity. This simulated vehicle can be moved over the simulated terrain in either the forward or reverse direction at a velocity V in one of three steering states corresponding to right turn, left turn, or straight. Steering dynamics correspond to those of the Phase I design with a steady-state turning radius of 5 ft. The transient condition in changing from one steering state to another is simulated by a second-order linear function for heading. For this simulation, the simulated vehicle had a track width of 0.71 meters and a velocity of 10 cm per second.

Experience in operating the test vehicle on a random slag course indicates that the actual path which a vehicle follows over a natural terrain

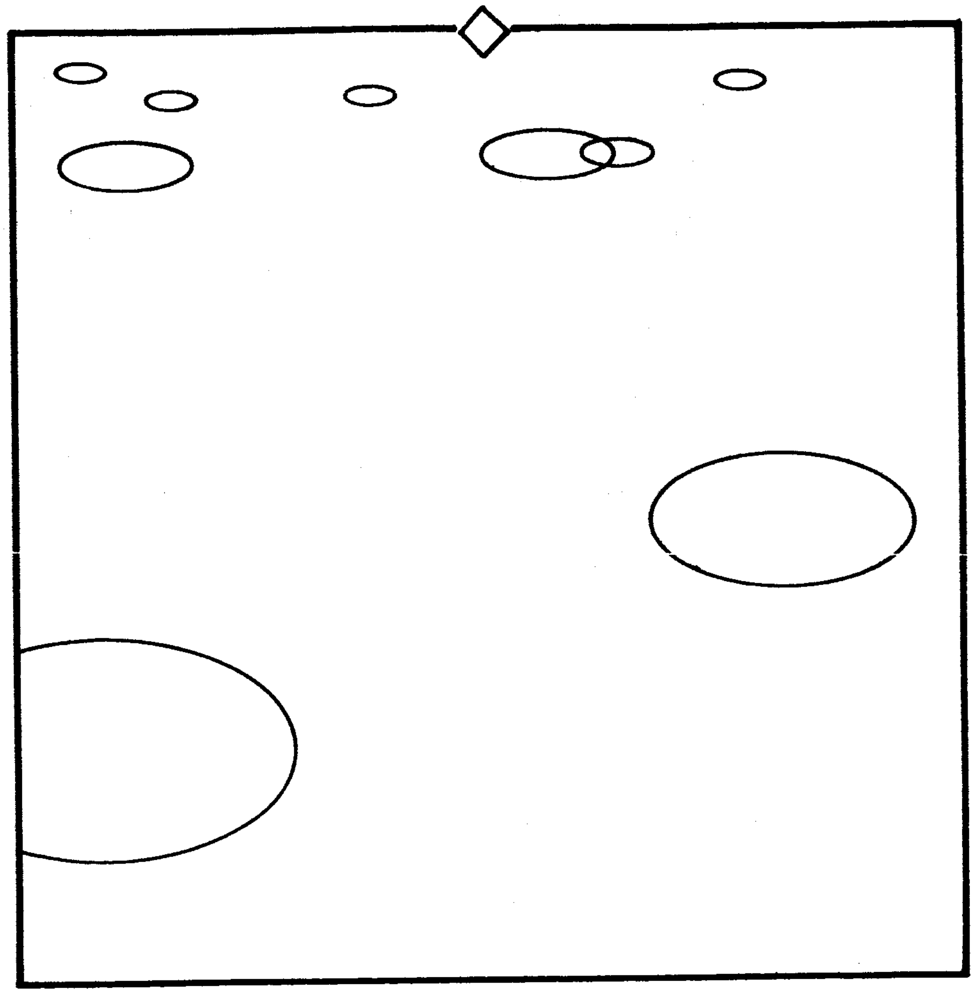


Figure 3-33 Typical View of Simulated Surface

deviates to some extent from a theoretical path. To simulate this condition, the actual path which the simulated vehicle follows is perturbed from the basic theoretical path. Vehicle perturbations can either be included or omitted in the simulation depending upon the state of a push-button on the COED console. Path perturbations consist of systematic and random perturbations, which are defined as follows:

1. Systematic perturbations depend on measurable surface characteristics and consist of a heading change and side slip, both linearly proportional to roll angle and related in direction so that the vehicle tends to turn away and slide away from a hazard area.

2. Random perturbations include heading and velocity changes; heading changes may occur every 10 cm of travel with a probability of 0.05, velocity changes may occur once every 10 cm of travel with a probability of 0.1.

For this simulation, systematic perturbations are related to vehicle roll angle which, in turn, is determined by the vehicle's proximity to a hazard area. Only the nearest hazard area influences vehicle roll angle. The induced roll angle is inversely proportional to the distance of the vehicle from the hazard area, but a roll angle can be induced for a considerable distance away from a hazard area. Maximum roll angle occurs when the vehicle center of gravity is on the edge of a hazard area. No roll angle is induced if the vehicle is exactly centered over a hazard area. The magnitude of these systematic perturbations for this simulation were such that the maximum heading change with respect to distance traveled, or dH/dS, was equal to 1°/cm. Likewise the maximum slip rate was 1 cm/cm. These maximum rates would, of course, only occur when the vehicle center of gravity was on the edge of a hazard area. Typically, if the operator is driving so as to keep the vehicle away from the hazard area, these maximum rates would never be encountered.

When a random heading perturbation occurs, it has a magnitude of -10° to $+10^\circ$ with a rectangular frequency distribution. Random velocity perturbations may have a value of from 0 to +V, with a rectangular frequency distribution. This velocity perturbation is a velocity increment added to the nominal vehicle velocity for 10 cm of travel. The heading and velocity perturbations are independent.

The simulation program provides a camera station located at a height H above the vehicle center of gravity. The pan and tilt angles are controlled by the operator from the COED console. Field of view is controlled by a program data card. For this simulation, the camera height was 1 meter and the field of view was 53° square. The simulation is designed for discontinuous rather than continuous driving; pictures can be taken only when the vehicle is stopped.

The actual path that the vehicle has followed is plotted on the view of the surface as the vehicle moves into the field of view. (The view of the simulated surface, i.e., the simulated TV view, remains constant while the vehicle is moved.) This plot of the vehicle's actual path is shown by rows of arrows in the case of forward motion and as rows of small circles in the case of reverse motion. Figure 3-34 shows the appearance of typical tracks plotted on the field of view. The vehicle's location is plotted by the display once for every 10 cm of movement in real time. It is possible to point the camera and maneuver the vehicle so that the actual path does not appear within the field of view, or to drive the vehicle out of the field of view. During normal operation, the vehicle must be moved forward a few feet before it appears within the field of view, the actual distance being a function of the camera field of view and tilt angle.

Path prediction, when used in the simulation, is shown by two rows of dots extending beyond the present vehicle position for a distance of 3 meters. These dots are spaced at 10 cm intervals. Every fifth and tenth dot is shown by a unique symbol to facilitate judgement of absolute distance. The predicted path is based on theoretical steering characteristics and does not anticipate vehicle path perturbations. However, its location is recomputed after every 10 cm of movement, always originating from the last reported vehicle position. Figure 3-35 shows a typical predicted path.

The simulation also includes the capability of inserting a transportation time delay in the control loop. For this simulation this delay was 3.2 seconds. It was intentionally made slightly greater than the delay due to communication transmission to and from the moon to allow for some amount of ground data handling delay.

The required direction of travel to reach the destination is shown by a diamond symbol on the edge of the field of view. This symbol, shown in Figure 3-35, shows the relative bearing of the destination with respect to the azimuth pointing angle of the camera. If the diamond is to the right

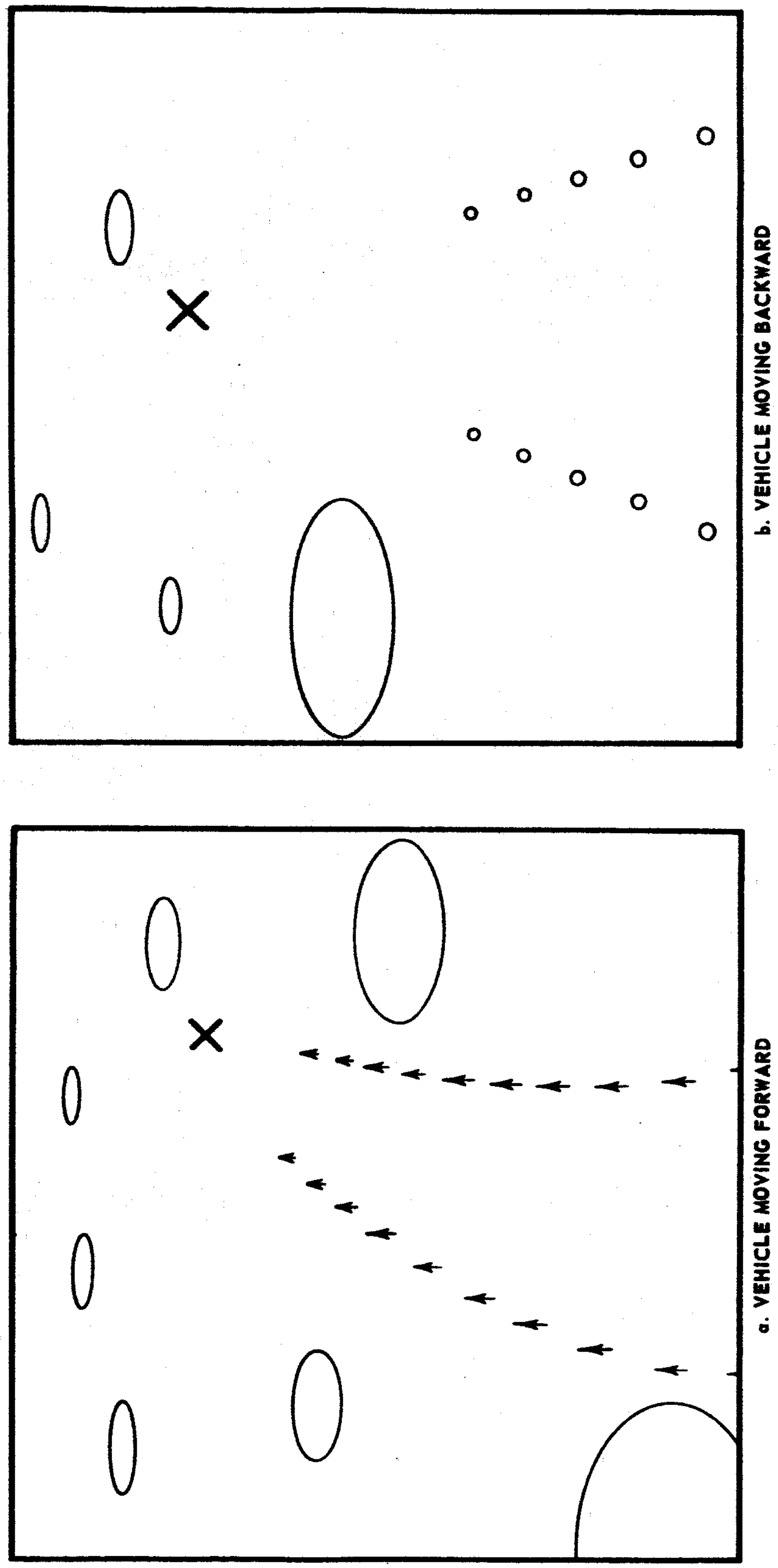
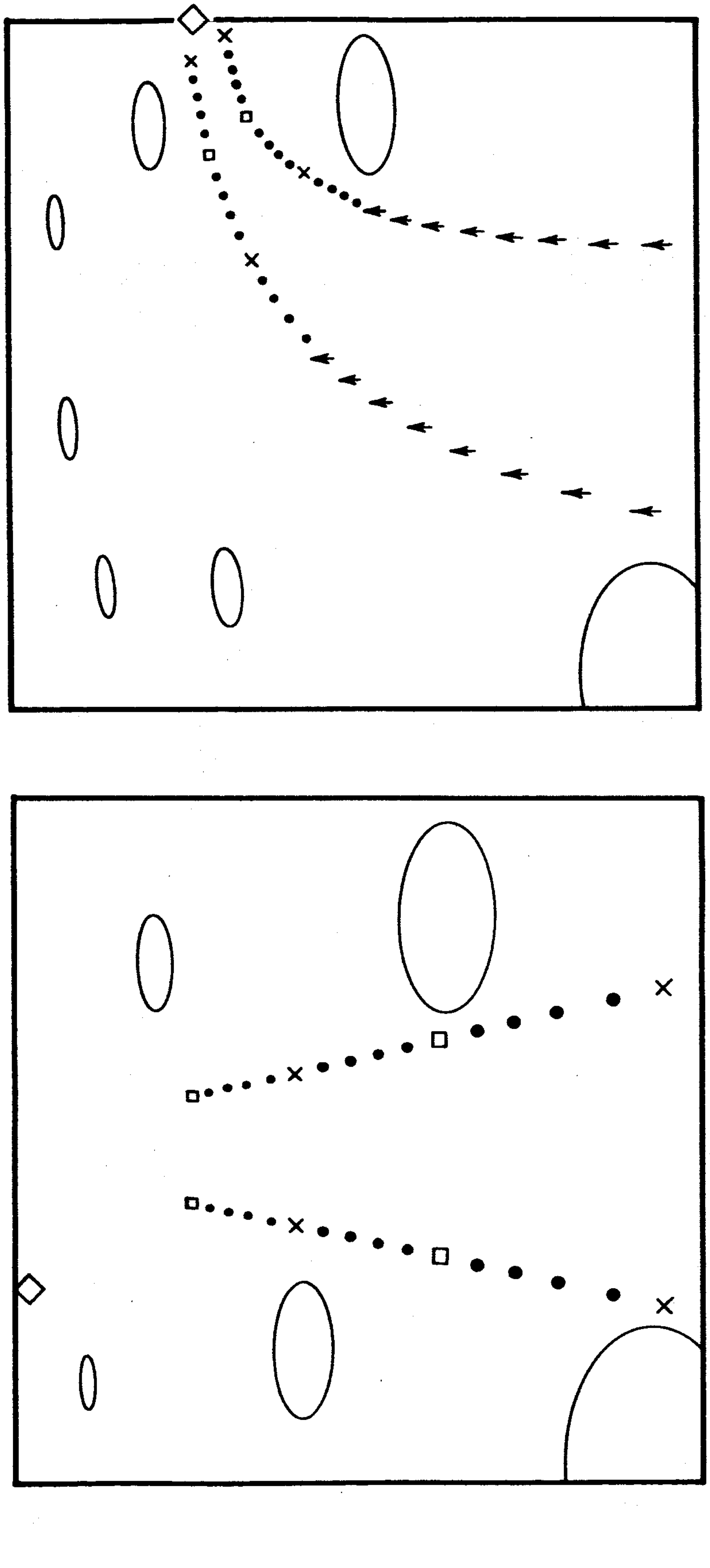


Figure 3-34 Plot of Actual Vehicle Path on Simulated Field of View



a. BEFORE VEHICLE ENTERS FIELD OF VIEW – STRAIGHT COMMAND

b. AFTER VEHICLE IN FIELD OF VIEW – RIGHT TURN COMMAND

Figure 3-35 Typical Predicted Path

at the top of the screen, then the destination is forward and to the right; if the diamond appears along the bottom edge of the field of view, the destination is behind the present field of view. The destination symbol is related to camera azimuth and not to vehicle heading. If the vehicle is close enough to the destination for the destination to be included within the field of view of the camera, then the destination is shown as an X.

3.4.4 Test Conditions

Subjects for the test were engineers assigned to the interim study. The six experimental conditions were selected by pushbutton controls on the COED console. In each case the subject's task was to drive the simulated vehicle from an initial starting point to a designated destination. Subjects were instructed to avoid running into the hazard areas at all costs but if they did encounter a hazard area they were instructed to stop immediately, back out, and go around rather than continue to drive through. Encountering a hazard area was indicated to the subject by the sounding of the computer horn. It was also indicated graphically on the display by the intersection of the vehicle's path with a hazard area.

The secondary mission objective of the subject was to reach the destination as quickly as possible. Several different sets of starting points and destinations were chosen so that a subject would never encounter the same path twice. Thus, there was no opportunity to learn the strategy appropriate to a particular starting point and destination set. In all cases the initial vehicle heading was pointed towards the destination. The straight line distance between each starting point destination pair was approximately 50 meters. In addition, each pair was chosen so that the resulting path was of approximately the same level of difficulty.

3.4.5 Operating Procedures

3.4.5.1 Closed-Loop Control

A picture was first requested by pushing the appropriate button on the COED console. Prior to requesting a picture, the subject could adjust the pointing angles of the camera. The time required for the computer to assemble and display a new picture after a request was 7 seconds for this simulation program, which approximates the time required to obtain a picture with the actual SLRV system.

Four pushbuttons on the front of the COED console controlled vehicle motion. A forward/reverse pushbutton determined the direction of travel. The forward/reverse button also determined the predicted path direction. The predicted path, when used, was displayed even when the vehicle was stopped, in which case the predicted path was based upon the last commanded steering state. The other three pushbuttons were designated left, straight, and right. These pushbuttons, when illuminated, indicated that the vehicle was moving in that steering state. If all lights were off, the vehicle was stopped. To stop the vehicle, the pushbutton that was illuminated was pressed. It was possible to change the steering state with the vehicle running.

3.4.5.2 Open-Loop Control

The subject adjusted camera pointing angles, requested a picture, and decided the nature and duration of a maneuver that he wanted to make for each step. This desired path was then related to the test administer in the form of so many seconds straight, followed by so many seconds right, etc. The test administrator would then blank the screen and give the requested command sequence to the vehicle by operating the vehicle control pushbuttons for the appropriate length of time. When the subject's desired maneuver was completed, the test administrator would press the new picture request button and only then unblank the screen. Thus, in open-loop control, the subject was not able to see where the vehicle actually went in the old field of view. This method of control does not rely on navigation data feedback while running.

3.4.6 Scoring Procedure

The simulation procedure was designed to accumulate several measures of performance:

1. Total distance traveled

2. Total running time

3. Number of pictures requested

4. Distance to destination at the end of the run

5. Number of hazard areas encountered.

Each entry of the vehicle into a hazard area constituted an encounter. It was possible for a subject to get into difficulty with respect to one or two hazard areas and, by successive forward and reverse maneuvers, to encounter one or two hazards many times.

The absolute magnitude scores obtained from the computer were then translated into four separate average scores, which were computed as follows:

1. $\text{Average velocity} = \dfrac{\text{total distance traveled}}{\text{total time}}$

2. $\text{Average step length per picture} = \dfrac{\text{total distance traveled}}{\text{number of pictures requested}}$

3. $\text{Average decision time per picture} = \dfrac{\text{total time - vehicle actual running time - picture time}}{\text{number of pictures requested}}$

4. $\text{Average number of camera adjustments per picture} = \dfrac{\text{total camera adjustments}}{\text{number of pictures requested}}$

The amount of actual vehicle movement time was computed on the basis of total distance traveled at the constant vehicle velocity of 10 cm/second. Picture time was computed on the basis of 7 seconds/picture.

3.4.7 Test Results

Results of the testing are shown in Table 3-25. Weighting factors were computed on the basis of scores of conditions 1 and 2 for average velocity, average step length, and average decision time per picture. Each weighting factor is based upon the ratio of the group mean to the individual subject's score on that condition and scoring measures. Weighting factors for conditions 1 and 2 were then averaged for each subject and used to adjust each subject's score on conditions 3 through 6. Thus the performance scores shown in the Weighted Scores columns of Table 3-25 on conditions 3 through 6 are normalized for individual subject differences as revealed on conditions 1 and 2.

The weighted scores indicate that closed-loop control is clearly superior to open-loop control. However, within open-loop control it appears that path prediction is not useful. Indeed, it seems to cause an increase in decision time with no appreciable increase in step length,

TABLE 3-25

NUMERICAL RESULTS OF PATH PREDICTION EVALUATION TESTS

Subject	Condition (from Table 3-24	Path No.	No. Hazards Hit	Average Velocity (cm/sec)	Average Step Length (meters)	Average Decision Time per Picture (sec)	Average No. of Camera Adjustments per picture	Weighting Factors			Average Velocity (cm/sec)	Average Step Length (meters)	Average Decision Time per picture (seconds)
								V	SL	DT			
A	1	1	1	7.43	3.73	5.94	0.63	0.995	1.046	1.198			
B	1	1	0	7.23	4.03	8.43	0.21	1.010	0.969	0.844			
C	1	6	0	8.16	4.73	3.58	0	0.895	0.825	1.985			
D	1	1	0	6.38	3.09	10.5	0	1.145	1.261	0.676			
Mean	1			7.30	3.90	7.11							
A	2	5	0	7.80	4.91	6.75	0.42	0.959	0.840	0.963			
B	2	5	0	6.78	3.40	9.16	0.17	1.103	1.211	0.710			
C	2	5	0	8.43	4.79	2.00	0	0.887	0.860	3.25			
D	2	5	1	6.90	3.36	8.08	0.16	1.084	1.228	0.805			
Mean	2			7.48	4.12	6.50							
A	3	3	1	2.38	0.65	14.7	0.51						
A	3	4	1	3.38	0.977	12.2	0.21	0.977	0.943	1.081	3.30	0.92	13.20
B	4	3	0	2.56	1.49	36.3	0.08						
B	4	4	3	2.10	0.878	26.0	0.54	1.057	1.090	0.777	2.22	0.956	20.2
C	5	3	14	5.60	3.59	21.2	0.67						
C	5	4	5	6.12	4.15	19.25	0.29	0.891	0.843	2.618	5.45	3.49	50.4
D	6	3	0	4.50	2.51	23.8	0.26						
D	6	4	0	5.98	3.40	15.9	0.38	1.115	1.245	0.741	6.66	4.23	11.8

resulting in a lower average velocity. One point of concern, however, in this comparison of prediction in open-loop control is the fact that subject B, who performed with path prediction, exhibited negative learning from the first to the second trial on his condition. This is contrary to the expected situation and to the performance exhibited by the other three subjects on their respective conditions. Also, the number of hazard areas encountered by subject B on his second trial would suggest that perhaps he had at some point made a strategy error and got into a difficult situation.

The value of path prediction in closed-loop control is indicated by comparison of the scores between subject C and D on conditions 5 and 6, respectively. This comparison indicates that path prediction is valuable in this mode of control. The actual magnitude of this value, however, is clouded by the fact that subject C had a large number of hazard area encounters. Since no rational penalty has been found by which the average scoring measures can be adjusted to correct for hazard encounters, the extent to which his performance might have been degraded had he operated more cautiously is unknown.

3.4.8 Further Test Results

The preceding COED test for discontinuous operation was designed to evaluate the relative performance of open- and closed-loop control, with and without predictive aids. The test showed closed-loop control to be superior to open loop control. However, for closed-loop control, no definite conclusion could be drawn regarding the merit of path prediction. If anything, performance was better without prediction, disregarding obstacle encounters. Unfortunately, a high number of obstacle encounters occurred for this case. This further confounded the matter, since any penalty imposed for encountering an obstacle would be purely arbitrary.

For clarification, further tests were performed for closed-loop control, with and without prediction. The same subject (Subject D) was used for both conditions. The other original subject (Subject C) was unavailable for further testing. The following definitions apply in addition to those originally defined in Section 3.4.6.

$$\text{Average step length per step} = \frac{\text{Total distance traveled}}{\text{Number of steps made}}$$

$$\text{Average decision time per step} = \frac{\text{Total elapsed time} - \text{total picture} - \text{total travel time}}{\text{Number of steps made}}$$

To gain further insight, the number of steps made for each run was counted. For this purpose, a step was counted for each picture in which the vehicle was moved. If several movements took place within a picture, it was counted only as one step. Counting the total steps for each run allowed computation of the average step length per step and the average decision time per step.

The five parameters listed above were used to evaluate the relative control performance. The higher the average velocity, the better the performance. Step length is inversely related to difficulty of vehicle control; as the operator experiences more difficulty in surface assessment or vehicle control, he tends to take shorter steps. Decision time significantly affects the average velocity; increasing decision time decreases average velocity. A long decision time generally indicates that the operator is experiencing difficulty. Therefore, a short decision time is desired.

Since Subject D was used for both cases, no weighting factors were required. This allows direct evaluation of raw data scores. The weighting factors for Subject C in the original test series were quite large on a percentage basis, adding to the uncertainty of the final results.

The test results are tabulated in Table 3-26. Comparing the performance with and without prediction, it can be seen that prediction definitely is beneficial. All performance indices show the improvement added with path prediction. Perhaps the most important is a 45% increase in average vehicle velocity. On an average, approximately two pictures were requested at each stop. This is reflected in the approximate factor-of-two difference between step length per picture and step length per step, and decision time per picture and decision time per step.

One further comment is in order. Path prediction significantly aids the operator in several additional ways which cannot be measured objectively. First, the predicted path motions at the outset of each step provide an indication of vehicle behavior in the picture blind spot. This allows better estimation of performance for the remainder of the step. Another benefit is better assessment of passage between or over obstacles. A third factor which plays a strong role is the reduction of operator stresses and anxiety, provided by prediction. The operator enjoys a more definite idea of vehicle performance at all times. This is particularly helpful in difficult areas where operation without prediction generally is marked by operator confusion and uncertainty.

TABLE 3-26

TEST RESULTS

Run	Path	Prediction	Velocity Average cm/sec	Average Step Length Per Picture, Meters	Average Step Length Per Step, Meters	Average Decision Time Per Picture, Sec	Average Decision Time Per Step, Sec
5	8	Yes	5.4	2.26	5.52	12.3	24.7
1	9	Yes	6.6	2.80	4.10	7.4	10.8
6	11	Yes	5.5	2.44	4.30	12.9	22.8
Avg.			5.8	2.50	4.65	11.9	19.4
2	7	No	3.3	1.35	2.82	20.2	42.3
3	10	No	4.6	1.58	2.37	12.1	18.1
4	11	No	4.1	1.54	3.01	15.4	30.1
Avg.			4.0	1.49	2.74	15.9	30.1

3.5 CLOSED-LOOP CONTROL

The COED test results are described in Section 3.4, including the comparison of open-loop and closed-loop operation. It is recommended that the vehicle be controlled in a closed-loop manner. In closed-loop control, the vehicle is controlled in real time by the operator, even though the vehicle operates fundamentally in a discontinuous mode. Closed-loop requires the ability to transmit navigation data and control commands from and to the vehicle, respectively, as the vehicle is in motion. Video data are not transmitted while the vehicle is in motion.

Closed-loop control increases average vehicle velocity by two means: increasing average step length, and decreasing average operator decision time. Of these, increasing the step length is by far the more important. Since mission time is inversely related to step length, the capability of long steps is of major importance to mission success. Closed-loop control eliminates the necessity of completely evaluating the surface and planning the step before committing the vehicle to motion. The operator can in effect extend the surface assessment period to include the information gained by monitoring the vehicle's progress. Further, by monitoring this progress, corrective actions can be applied as required to maintain the vehicle on the desired path. Both of these factors allow the operator to utilize longer steps. The operator can employ an adaptive strategy as the vehicle moves along, rather than being subject to an inflexible strategy based on less information.

It should be noted that closed-loop control is of most benefit when short steps are required. Increasing an average step length from 4 to 5 ft produces a significantly greater reduction in mission time, either on a percentage or actual magnitude basis, than does increasing an average 9-ft step to 10 ft. In the ETM tests, the most common step length, neglecting crimp turns, was 4 ft. It is the opinion of the operator and driver that an improvement of at least 1 ft and perhaps 2 ft in average step length could have been obtained with feedback data and closed-loop control.

As stated previously, the 4 ft average step used in the ETM tests represents a minimum condition. As the surface roughness decreases, longer average steps will result. The resultant increased travel time will increase the total time period over which corrective actions can be made. Although the improvement is not as striking as with short steps, closed loop control still can shorten mission time appreciably.

Closed-loop control raises two problems in implementation. First, a tight control loop is quite important. To achieve this, the total loop delay must be kept as small as possible. This in turn implies an automatic steering command formatting system, with direct hard-wire or RF link between SFOF and Goldstone. This is discussed in detail in the Phase I Final Report (BSR 903) and in Section 4.6 of this report. A second consideration is the influence of navigation accuracy on step length. In this case, navigation errors only with respect to the step origin coordinates are of interest. Errors can be expected to accrue directly with step length. If these errors become significant, the benefits of closed-loop control will be negated for long step lengths. A need exists to study the effect of navigation errors on step length. This could be done readily on the present COED SLRV simulation with minor program changes.

SECTION 4

GROUND DISPLAY AND CONTROL

4.1 SUMMARY

The requirements for ground display and control equipment and the analysis of critical ground operation activities and times considered initially in Phase I have been reviewed and updated to reflect the results and conclusions of this Interim Study. In general, the current concept of ground display equipment, especially that associated with vehicle control, requires a more sophisticated system than that depicted in the Bendix Phase I Final Report. This increased sophistication is associated primarily with the requirements to provide simultaneous display of multiple images of the lunar surface and to provide these images stereoscopically so that they may be viewed comfortably and with correct geometric scaling from their center of perspective. Present estimates of critical ground activity and associated operation times are essentially identical to the Phase I estimates—two minutes per interpoint step exclusive of vehicle, antenna, and camera movement times and picture transmission time.

Neither the present estimates of ground display and control requirements nor the present estimates of ground operation activities and times should be considered final. Considerable additional effort involving extensive testing and experimentation is required before operational procedures and operational equipment are finally defined. Major questions yet to be answered concerning the design of ground display equipment are associated with: (1) the operational effectiveness to be gained through stereo display with surface assessment by operator judgment as opposed to monocular display and photogrammetric interpretation of the surface, (2) the operational effectiveness of such synthetic overlays as actual or predicted paths or scaling grids for the operational situation, and (3) the performance gained by viewing the images from their center of perspective. Alternate design concepts for the vehicle communication subsystems are being considered; these could drastically reduce the number of required ground activities and thus the amount of critical ground operation time associated with obtaining TV pictures of the surface. Subsequent paragraphs in this section discuss ground display requirements in support of vehicle control as they are presently understood and present implementation concepts applicable to these requirements. The section is concluded with an updated ground activity and time line analysis.

4.2 OPERATING CONCEPT AND GENERAL REQUIREMENTS

Consideration of various control concepts and procedures during this study has lead to confirmation of the Phase I conclusion that closed-loop control is required. This conclusion holds even though vehicle subsystem design constraints may restrict operation to discontinuous control where optical images of the surface are obtained only when the vehicle is stopped. Thus, there is very little difference in ground equipment requirements between either discontinuous or continuous control. Both require an automatic command formatting and transmission capability similar to that recommended in Phase I as well as on-line data processing of telemetry data with about one second maximum input-to-output processing delay. Computation requirements in support of closed-loop control were examined in Phase I and were detailed in the final report, Section 13.4, Volume III.

Table 4-1 summarizes ground display and control requirements derived from the conclusions and recommendations of this study. To the extent that differences exist, the requirements are based upon discontinuous control. The hardware implications of these requirements are discussed in detail in subsequent sections.

4.3 MAIN DRIVER DISPLAY CONSIDERATIONS

The main driver display, if defined as a hardware subsystem, is the most important and sophisticated subsystem of the mission-dependent ground operating equipment. Under present concepts of task allocation within the ground operating complex, this main display would be located at the vehicle operator's (driver) work station. As a hardware subsystem, the main display is presently considered to include all equipment necessary for presenting optical images of the lunar surface together with the necessary synthetic data overlays. The following subsections discuss in detail various factors which must be considered in the design of the necessary display generation equipment and, where appropriate, make recommendations for approaches to implementation.

TABLE 4-1

SUMMARY OF GROUND DISPLAY AND CONTROL REQUIREMENTS DERIVED FROM THE INTERIM STUDY

1. A capability for simultaneous presentation of two or three optical images is required; these will typically be horizontally adjacent images. (This, in essence, reflects the requirement for a horizontal field of view (fov) of the order of 100 to 150°. Such an fov can be developed on the ground by side-by-side display of two or three images).

2. A capability for rapid recall of optical images taken at the present and previous vehicle location in required.

3. Stereo display of all optical images is presently considered necessary. This display must create a dimensionally accurate 3-dimensional image of the surface in perceptual space for the observers and should be comfortably viewable for periods of at least two hours.

4. Synthetic data overlays on the optical images will be required. Required items of synthetic data are as follows:

   a. Bearing to destination, with respect to picture azimuth

   b. Vehicle heading, with respect to picture azimuth (may be combined with d below)

   c. An indication of the orientation of a horizontal plane through the stereo image of the surface.

   d. A predicted path indicating the path along which the vehicle will tend to move based upon a specified steering state.

   e. Actual vehicle path plotted in real time as the vehicle moves in the field of view.

5. A capability for establishing the overall scale of each scene by establishing an accurate range to one or more image points will be required if the accuracy of surface assessment by observer judgment cannot be greatly improved over that measured in this study.

TABLE 4-1 (CONT.)

6. An integrated symbolic representation of vehicle steering angle, camera azimuth, and bearing to destination on a separate indicator may be necessary in addition to display of similar information superimposed on the optical images of the surface.

7. A planimetric map sketch of the surface along the vehicle's path would be desirable for backing out of a difficult area, for strategy and mission planning, and for navigation.

8. A control capability for rapidly selecting preselected camera pointing angles in addition to a capability for variable control of camera pointing will be required.

9. Continuous control of vehicle steering while the vehicle is moving rather than canned or fixed mobility command sequences will be required. (Two commands per second are sufficient for "continuous" control). Also, a control capability is required to establish maximum steering angle while the vehicle is stationary so that a minimum radius turn can be initiated immediately upon moving. Continuous control while the vehicle is moving requires holding the display of the optical images at least until the step is completed.

10. The viewing distance to the optical image display should be greater than that used to view the stereo TV in this study program in order to reduce visual fatigue. (The observer attempted to view from the center of perspective which was about 15 in. in front of the screen.)

11. Individual picture elements of the optical images should be large enough so that adjacent elements are tangent to each other and thus are not a distraction.

12. The operator concerned with driving should not be assigned tasks not directly related to assessing the surface and moving the vehicle. For example, engineering performance monitoring should be performed by a separate operator. (The Phase I operator task assignments were essentially confirmed.)

13. Only that information essential to driving should be displayed at the vehicle operator's position. Information not integrated with the optical images should be displayed adjacent to these images in a compatible manner. Looking away from the stereo model or removing stereo glasses (if required) to view secondary displays must be avoided.

4.3.1 Single vs Group Display

Experience in vehicle remote control gained during this study indicates that the tasks of surface assessment, control of the TV camera (or other optical sensor), and vehicle mobility control can be handled adequately by a single operator. These tasks are, however, sufficiently complex and mentally demanding as to require essentially the full time consideration of the operator. Any lull in driving activity is best used as a time of relaxation for the operator and not as an opportunity for inserting additional monitoring or control tasks. Therefore, tasks relating to monitoring or fixing the vehicle's position in lunar coordinates (navigation), control over collection of scientific or topographic survey data, mission planning and monitoring of mission progress, monitoring of the various supporting ground activities, and coordinating the ground operation as a whole should not be added to this vehicle operator's set of tasks. Some thought has been given to the possible need for an operator to assist in surface assessment. Such an assistant would be required if profiling of the surface from stereo images were required. Gross profiling, or cross-sectioning, of the surface might be necessary to establish the general contour of the surface. In addition, detailed profiling of the surface along a postulated vehicle track is being considered as one means of evaluating the vehicle's ability to traverse that path. (See appendixes A and B of the Interim Technical Report for an explanation of "profiling".) Either of these profiling tasks would require a specially trained operator and preferably a separate and independent display. Thus, for the most part the main display is intended for use by only one operator.

Two exceptions are expected to exist on occasion, however. The general mental strain and fatigue caused by the responsibility for controlling the vehicle together with the visual fatigue occasioned by viewing of stereoscopic images is expected to require a rather frequent change of vehicle operators. Present estimates are that a change will be required on the order of every two hours and this only if there are occasional brief periods of rest for the operator. To avoid a delay in mission activity upon changing drivers, it would be desirable if the new driver could view the driving operation over the shoulder, so to speak, of the present vehicle operator. Also, it is expected that the vehicle operator will not be the final authority on how and where to drive the vehicle. Rather, it is expected that he will control the vehicle in accordance with certain standard operating procedures, strategy rules, and safety factors. (The latter may be more qualitative than quantitative.) If a situation is encountered which cannot be met with the prevailing operating strategy or if there is some considerable risk in losing the vehicle if a planned course of action is pursued, then it is expected that the vehicle operator would defer decision to a higher authority such as a mission or program director. In this situation, it may be necessary for several people including the vehicle operator to view the display simultaneously in order to decide upon the best course of action. Thus, it is concluded that the main display for the vehicle operator should be designed primarily for a single observer but should be capable of being viewed on occasion by a small group.

4.3.2 Display Size and Viewing Distance

The required size and viewing distance of the main display are crucial factors in the design of the main display. These factors plus camera base line and convergence angles are the primary factors involved in controlling the geometric scale of the perceived scene.

The fact that scene geometry can be correct and undistorted for only one viewing position and then only if the camera spacing is equal to the observer's interocular spacing is well documented in the literature.* This single correct viewing position is the monocular center of perspective or the point at which the display image suspends the same angular fov for the observer as the object scene did for the camera; i.e., the image suspends an fov for the observer equal to the camera fov. Tests conducted during this study attempted to achieve this center of perspective viewing position as closely as possible. However, the limited scope of the study did not permit exploring the effect of viewing distance as a controlled parameter on performance. Thus, there is presently no way of knowing the extent to which a variation from this viewing position affects such parameters as accuracy of surface assessment, driving decision time, or probability of success. Such a controlled experiment should be made in the near future since, as will be seen in a moment, this requirement together with the large fov now required somewhat complicates the mechanization of the main display.

The location of the stereo model in display space is primarily a function of camera convergence angle. In general, all objects in front of the plane of convergence in object space should appear in front of the display

*References are located in Section 4.3.10

screen. All objects lying behind the plane of convergence in object space should appear behind the display screen. Parallel cameras represent a special case of zero convergence in which case the plane of convergence is at infinity; thus, all objects lie in front of the plane of convergence and should appear in front of the display screen. This condition was frequently observed during this study. Just as often, however, the stereo model appeared behind the display screen for parallel cameras. No explanation has as yet been found to explain this latter perceptual situation. It is another indication of the fact that there is still a lot to be learned about the formation and perception of stereo images.

Assuming that center-of-perspective viewing is required and maintained, the influence of viewing distance by itself on formation of the stereo model in perceptual space must be determined. Two possibilities for viewing distance by itself serving as a cue in depth perception within the stereo model come to mind. First, if the subject is aware of the distance to the viewing screen, he may have a tendency to imagine all objects in or near the plan of the viewing screen to be at the viewing distance. On this basis, the viewing screen should be at infinity for parallel cameras or at least beyond the maximum distance of any object in the scene. This would require a viewing distance of 20 ft or more and would be rather impractical. Second, accommodation, or focus, is generally considered a cue in space perception. It is impossible to incorporate the proper focus cue into the synthetic stereo model. It would seem intuitively that the viewing screen should be set at a distance which would provide a compromise between near and far focusing rather than requiring the observer to focus either on a near plane or on a far plane. Thus, on the basis of focus, it would seem the viewing screen should be located of the order of perhaps 6 to 10 ft away from the observer.

The operator concerned with surface assessment during the vehicle test portion of the study viewed the stereo TV screen from a distance of approximately 15 in. in order to view from approximately the center of perspective. This observer felt that this close viewing distance was uncomfortable and that the viewing distance in the operational system should be somewhat greater. It is not known whether this subjective opinion was caused by the requirement to maintain focus on such a close distance or whether it was associated with the requirement to dissociate accommodation and convergence reflexes in order to fuse foreground objects. The requirement to dissociate accommodation and convergence reflexes is an inherent problem in the perception of synthetic stereo models. The problem exists for any viewing screen distance and any camera convergence angle. We believe that this part of the perceptual problem can be eliminated through training and experience.

A display screen which would subtend a 120° horizontal fov at a viewing distance of 10 ft would have an arc length of about 20 ft. The vertical height of this screen would have to be about 9 ft to accommodate a 50° vertical fov. Problems associated with projecting images on such a screen become rather formidable. Projectors and observers must be located so that there are no interfering shadows (one upon the other), a large facility is required, and for this application, problems associated with locating other indicators, displays, and controls associated with the driving task are increased. There is some evidence to the effect that the observers head tilt angle influences judgments of slopes. To the extent that this observed phenomenon is valid, the observer's head tilt angle should approximate the tilt angle of the camera for proper perception of slopes. This would further complicate the display geometry and preclude the conventional movie theatre type arrangement in which the head is normally vertical or slightly tilted up while watching the viewing screen.

In general, the display must be such that:

1. The stereo model perceived by the observer is geometrically correct.

2. The stereo model is comfortably viewable for periods of at least two hours or more.

3. The implementation is practical and provides a work space compatible with the other tasks associated with vehicle control.

These are problems which beset the 3-D movie industry some years ago and contributed to the failure of that venture. They are not overcome simply by selection and training of operators. A person with good stereo perception is likely to be more sensitive to distortions and inconsistencies in the stereo model than one who has poor stereo perception. It is felt that any practical system will be a compromise between the various requirements. This compromise can only be arrived at through further study involving extensive testing of various configurations. It is not sufficient merely to create a stereo effect. The stereo model must be distortion free and scaled according to normal experience if accurate surface assessment is to be made by operator judgment.

4.3.3 Single or Multiple Image Presentation

The display requirement resulting from this study of presenting two or more images simultaneously is intended primarily to be a means of synthesizing a wide horizontal fov. A horizontal fov of 140° could be obtained with only two 70° images, if they were taken with the proper camera pointing angles such that the two images were adjacent along the centerline. Display of these two images in an integrated manner would then be relatively straightforward. To implement this capability on the ground, the axis of rotation of the cameras must be perpendicular to the center of the camera base line, and the relative angle between the principal axes of the two views as well as the fov should be constant such that the two images are exactly tangent at the point of overlap. If these simple rules are followed, the two stereo images will merge at the point of tangency. Multiple image presentation will be more effective if produced by a projection system rather than by separate direct view cathode ray tube displays of the separate images. A projection system to accommodate this requirement is complicated somewhat by the fact that multiple image display is not always required or desirable. There will be many times when a single image must be displayed. In this case, the image should be projected in the center of the viewing screen.

4.3.4 Method of Stereo Image Separation

The requirement for stereoscopic presentation of optical images requires some consideration of the method by which the images are separated, one presented to each eye of the observer. Of the numerous methods that have been tried at one time or another, three seem worthy of consideration for this application. They are anaglyph (color separation), polarization separation, and optical separation. The anaglyph technique involves producing one image of the stereo pair in one color, typically red, and the other image in a complementary color, typically blue or blue-green. The observer then views the presentation through corresponding color filters so that one eye sees the red image and the other sees the blue or blue-green image. The resulting image is usually perceived in black and white. This was the technique employed with the 3-D television system used during the vehicle test program portion of this study.

Polarization separation is similar to color separation except that polarizing filters are used instead of color filters. The polarization must of course be linear and mutually perpendicular for the two images. Usually the axes of polarization are set at 45^{o} to the vertical rather than vertical and horizontal so that the presentation to both eyes will be similar when the observer views objects in the space around him. Both the anaglyph and the polarization separation techniques permit the images to be viewed from a large number of positions, although the scene will appear geometrically correct for only one viewing position.

Optical separation is a term applied to those classes of devices which separate the two images of a stereo pair by means of lenses, prisms, or mirrors. They all require that the observer hold his head in a definite position in order to view the images, and only one observer can view the images at a time. Conventional instruments of this type employ a definite eyepiece . More sophisticated instruments of this sort may not have a definite eyepiece but still require that the observer's head position be in a fixed spatial location in relation to the apparatus. There is no question that the optical separation technique is capable of providing the most complete and most comfortable separation of the two images and thus the best stereo model. These advantages, however, are felt to be off-set by two disadvantages. The first disadvantage is that the observer's head is constrained to a fixed position. Viewing display information not integrated in the pictorial scene would be difficult and tiring with optical separation of stereo images, particularly if an eyepiece apparatus were used. Secondly, the restriction on number of observers which can view the same image simultaneously is considered a severe handicap in view of the previous discussion in Section 4. 3. 1 which concluded that simultaneous viewing of the same display by several observers would occasionally be required. A viewing device using optical separation of images would be appropriate for a support operator whose task is to provide photogrammetric scaling or profiling and photointerpretation of the images, but it would not be appropriate for use in the main display.

Both the anaglyph and polarization separation techniques also have their shortcomings, and the problem is selecting the lesser of two evils. Problems with these two techniques are generally similar and differ mainly in the magnitude of the various problems. Both techniques suffer severe light loss with the result that images must be viewed in a darkened area. Also, light entering the observer's eyes from the side or reflecting off the back of the special glasses used for viewing the stereo images produces an annoying distraction. This latter problem could be avoided in either case by use of specially designed glasses which block the entry of all light except that which enters through the filters.

Factors in which the two techniques are not equal are binocular rivalry and ghost suppression. Binocular rivalry occurs when the images presented to the eye differ in some gross respect such that they are regarded as incompatible. When this occurs, first one image and then the other will be suppressed in an alternating sequence. This condition manifests itself in the anaglyph technique by the observer noting a color cycling in the perceived scene. For example, if red and blue images are used, the subject will notice an alternation from blue to white to red to white to blue, etc. This color cycling was noted by many observers in viewing the anaglyph presentation used during this study program. The rate of color cycling observed was less than one cycle per second. There were indications, however, that the tendency for this condition to exist could be minimized by reducing the amount of color separation between the two images, in this case by adding green to the blue image. Also, this tendency for color cycling seemed to dissappear with extended viewing, thus suggesting that perhaps there is some ability to adapt to this condition. It was noted in this study that an exact color balance producing a black and white image generally could not be achieved without adjustment of the relative magnitudes of the blue and red images for each individual observer. This is a disadvantage for simultaneous viewing by several observers.. This problem of binocular rivalry also exists if the observer keeps his anaglyph glasses on and views colored objects other than the stereo images. The greatest problem arises when objects are of the same colors as those used in the colored filters. In this case, one eye sees one set of objects and the other sees a different set of objects. The total experience is one of considerable discomfort, and the observer is inclined to want to remove his anaglyph glasses quickly when looking away from the stereo images. This problem for this application can be minimized only by very careful design, with respect to color, of the entire work place environment. The problem of binocular rivalry does not exist with the use of polaroid filters when viewing the stereo images and is easily eliminated for viewing other objects by orienting the axes of polarization at 45° rather than vertical and horizontal.

A ghosting problem arises when the filtering, either color or polarization, is sufficiently imperfect that one eye sees some of the image intended for the other eye. Ghosting was at times noticeable with the anaglyph TV used during this study, particularly when green was added to the blue image to reduce the color-cycling problem. Experimentation with various combinations of color filters tended to minimize the ghosting problem with the apparatus used in this study. Ghost images are more apparent in areas of high contrast and can be very distracting and annoying. Ghosting is an inherent problem with the anaglyph technique, because existing technology does not permit the production of dyes, pigments, and phosphors with sharp spectral cutoff characteristics. Ghosting can also be a problem with polarization separation, however. In this case, the mechanical alignment of the axes of polarization is more of a problem than is the production of the filter material itself.

Polarization separation is presently considered the best of the various techniques for separation of the images at the main display.

4.3.5 Image Registration

The accuracy with which stereo images must be registered in the display apparatus is of interest to the design of the display equipment as well as to the design of the optical components in the image sensors on the vehicle. The general operating procedure during this study was to keep the two images registered as accurately as possible. Although no formal tests were made, it was observed during the study program by viewing both the stereo TV and the stereograms that vertical displacement, rotation, and size or magnification differences between images could be accommodated to some extent without disturbing the stereo model. As these types of distortions are increased, first eye strain is noticed and then loss of fusion of the images occurs. The amount of misregistration that can be tolerated for initial fusing of the images is less than that for retaining fusion. From the experience gained in this study, it would seem that registration with respect to vertical displacement, rotation, and image size should present no problem in mechanization. It is believed that vertical displacement on the order of several picture elements, rotation of a couple of degrees, and size differences on the order of 2 to 5 % can be accommodated by the observer. The importance of these parameters should be specifically explored in future studies with particular attention given to long-term visual fatigue occasioned by picture misregistration.

Horizontal misregistration of the pictures gives rise to a fixed bias in the picture parallax which provides the stereoscopic depth cue. If one supports the notion that the eye's convergence angles do not aid in localizing a stereo image in perceptual space, then horizontal displacement would not affect perception of the stereo model so long as the images could be fused. While this notion that convergence angles do not of themselves aid in depth perception is a hypothesis existing in some academic circles, there are also those who feel just the opposite, i.e., that convergence angles do aid in localizing that image in perceptual space even though the observer may not be able to describe what these angles are. Observations during this study tend to support this latter opinion. Therefore, it is presently concluded that horizontal displacements can not be tolerated without sacrificing distortion in the stereo model. It is recommended that horizontal registration be held within less than one picture element in width.

The previous discussion pertains just to the registration between two images. If synthetic data such as scaling grids or predicted paths are to be overlaid on the lunar surface scenes and if these aids are to be presented stereoscopically in proper geometric relation to the surface scene, then they must be accurately registered. For example, if a horizontal grid is to be placed in the scene, horizontal misregistration causes the grid to appear to move vertically with respect to the surface, vertical misregistration affects the accuracy of the range lines with respect to the original camera station, and rotation affects the accuracy of the plane of the grid with respect to a horizontal through the image scene. Numerical accuracies on the registration of synthetic data have not been explored and should be a topic for future investigation.

4.3.6 Picture Storage and Retrieval Requirements

A conclusion of this study is that rapid retrieval of previous optical images is required. However, with respect to vehicle control, this image retrieval requirement pertains primarily to images taken at the present and last one or two previous stop points. Images older than this are not expected to be of much use to the direct problem of vehicle step control, but are expected to be of considerable importance to such other mission activities as navigation, mission and strategy planning, and topographical surveying. For control purposes, recalled images should be presented in the same manner as current images are presented. Considering the number of pictures taken per stop during the vehicle test program portion of this study, a capability of retrieving any of the 10 most recent images should be sufficient for vehicle control purposes. Other activities previously mentioned must be capable of retrieving images taken any time during the mission. It is likely, however, that they may be able to use hard copy photographs of the images. This was the approach chosen in Phase I for storing and retrieval of images relating to land mark identification in support of navigation. A hard copy photo recorder was included in the navigation portion of the survey console along with a place to file these landmark images conveniently.

The most versatile type of storage and retrieval system would be a magnetic disc memory system. A single image, or perhaps stereo pair of images, together with all appropriate reference data could be stored on a single track. Retrieval of any desired image could be made rapidly on the basis of any one or combination of reference data parameters. If the image data were digitally encoded, the disc memory system could be associated with a general purpose digital computer such as those already existing at the SFOF. This approach was considered briefly in Phase I, and still appears attractive and worthy of future detailed consideration.

4. 3. 7 Picture Display Time and Method of Image Generation

Optical images are obtained on request of the operator and are fundamentally still views. Transmission time for a stereo pair from the vehicle will be several seconds with the exact time being dependent upon the exact design of the communication subsystems on the vehicle. The ground equipment must process these image data and present an image which can be viewed continuously for as long as the image is required by the operator. Data from this study indicate that the vehicle control operator may view a picture for as little as 5 seconds or as much as one or two minutes before he decides either to request another picture or commit the vehicle to motion. The display equipment must, at the minimum, hold the picture for this surface assessment time. Ideally, however, the last view taken before the vehicle is committed to motion should be held until the vehicle has completed its step and the next picture has been requested and is available for presentation. This procedure would provide better continuity in allowing the operator to relate the present situation with the previous situation. Considering all the various activities that must occur on the ground when the vehicle is stopped, based upon Phase I design concepts, and the new surface assessment time data obtained during this study, the average total time per step is estimated to be about three minutes. Ground equipment should be designed to hold the display somewhat longer than this estimated average time. Thus a minimum display time of five minutes is considered a requirement.

Two practical alternatives exist for image generation: scan conversion and photorecording with rapid processing and projection. Electronic scan converters would be similar to those now at the SFOF for the Surveyor Program. Advantages of the scan converter approach are:

1. The image is immediately available for readout as it is being received.

2. A single scan converter can drive many conventional closed-circuit TV monitors for multiple viewing in various locations.

3. Scan converters of the type required are readily available with minimum development.

4. The display would be electronically generated and the viewer could have the usual contrast and brightness controls to adjust for maximum image quality.

The main disadvantage of the scan converters is the fact that the reproduced image is degraded in quality with respect to the input, and that this degradation increases with storage time. This deterioration is primarily in terms of reduced picture contrast and a white spot which forms near the center of the picture. Recent developments of scan converters minimize these problems so that for input pictures with resolution of about 350 TV lines there is negligible deterioration for at least the first three minutes of storage time. Another disadvantage of scan converters is associated with the requirement for stereo pairs. Proper reproduction of stereo images would require that both write and read deflection circuits in the two scan converters have to be matched.

Film recording with rapid processing and projection offers the potential advantage of maximum quality of image reproduction coupled with essentially unlimited viewing time, and if a single recording CRT were used with sequential transmission of images there would be no problem in matching deflection circuits since only one image reproducing device would be used. Disadvantages of the film recording method of image generation approach are:

1. Although the basic film recording, processing, and projection technology exists, the necessary equipment is not nearly off the shelf and would require considerable development.

2. The equipment is complex, and requires daily maintenance.

3. Picture contrast can not be adjusted by the operator while viewing the image.

4. Film processing time would produce a delay in viewing the picture of the order of 5 to 10 seconds. Although this may seem trivial on a per picture basis, it tends to make an excessive mission time even worse.

These and other image generation techniques were considered briefly during Phase I at which time the film recording technique was chosen primarily on the basis of the assumption that maximum image quality would be necessary. Experience during this study with the color TV monitor indicates that that quality of an image is acceptable for driving operations, at least to the extent of this study experience. Scan converters would provide comparable image quality for the required time period. For those few occasions when long display time is required, the images could be erased and rerecorded by recalling the image data from magnetic disk storage.

Previous discussions in Section 4. 3. 2 concerning display size and in Section 4. 3. 3 concerning multiple image presentation indicate that at this time the best apparent method of displaying the images is by means of projection on a viewing screen. If future studies show that a reasonably small flat screen can be used, then rear projection would be feasible and desirable. If a large screen is required and if the screen must be curved towards the observer in order to present the necessary wide field of view with multiple images, then front projection will be necessary. The considerable increase in complexity of projection TV as opposed to conventional direct view TV monitors demands that further study and experimentation be devoted to verifying the need for this requirement before a large screen projection system is definitely decided for the operational system.

4. 3. 8 Picture Display Rate

If optical images of the lunar surface are obtained only when the vehicle is stopped and if each image, or stereo pair, is obtained on discrete command from a ground operator, then the time required to obtain and display these images does not affect performance of the remote control task per se. These times do of course influence total mission time and are included in mission time analyses. Since each image requested is typically different from the previous, each image should be treated as a still picture. Sequential display of these images would be more effective for vehicle control purposes if the entire image was first assembled on the ground and then displayed in its entirety rather than displaying each picture element as it is being received. This would not be true however for those operators concerned with performance monitoring. These operators should be able to view the picture as it is being transmitted since if the picture is obviously of poor quality, action to adjust and request a new picture could be taken without waiting for the complete transmission of a bad picture. The rate at which pictures are requested and thus displayed to the vehicle control operator is expected to be under his control. Tests during this study program indicate that the operator may take as few as five seconds or as long as one or two minutes to examine a single picture, or stereo pair. If the operator decides he needs a new picture, a considerable time lapse will occur before that new picture is available for presentation. It seems desireable to consider an operating procedure which would provide for taking several pictures at standardized locations in accordance with a fixed procedure. These several pictures would be stored on the ground and would be available for quick retrieval by the vehicle operator as desired.

The only other display rate problem which must be considered in mechanizing the display system is that of ensuring a flicker-free display. Flicker is a non-existent problem with the photorecording processing and projection technique of display generation. It is also not a problem with the scan conversion technique if standard closed-circuit TV frame rates are used for the output. Flicker, however, can be a problem with regard to the synthetic data overlays that must be generated and superimposed upon the pictorial images. In this case the problem is eliminated by ensuring that the display re-write rate for synthetic data is compatible with the decay characteristics of the display medium. For example, if the synthetic data are presented by means of a projection CRT using a P4 phosphor, then the synthetic data should be rewritten 60 times per second on the face of the CRT to ensure a flicker-free presentation.

If vehicle subsystem designs should be modified to permit transmitting of images while the vehicle is moving, then additional picture scan rate problems must be considered. The problems that would be encountered are related to picture smear and motion discontinuity. Assuming a shuttered optical sensor, picture smear occurs if the sensor is moving, due to vehicle motion, while the shutter is open. Distracting and fatiguing motion discontinuity in a sequence of what might be intended as motion pictures is expected to occur if a given image element changes its location by more than a few picture elements from one frame to the next. It is expected that a relationship could be found that would require essentially a constant ratio between vehicle velocity and picture rate for continuous movement of the vehicle.

4.3.9 Synthetic Overlay Requirements and Methods of Generation

Synthetic data overlay requirements for the main display were listed in item 4 of Table 4-1. Bearing to destination indicates the desired direction in which the vehicle should be moved to reach some ultimate destination. This destination may be either the next point to be surveyed or some intermediate objective established by mission planning. In any case, it tells the vehicle operator which way he should try to move the vehicle. Long range strategy planning is not considered a part of the vehicle operator's task. Bearing to destination should be integrated with the pictorial images as a symbol located on the edge of the scene. This symbol should indicate the relative bearing to the destination with respect to picture azimuth.

Vehicle heading with respect to picture azimuth need not be displayed as a separate piece of information, but could be integrated with a predicted path. A predicted path indicates the direction in which the vehicle would tend to move with respect to a given scene and is in fact the exact information that the vehicle driver is concerned with.

An indication of the orientation of a horizontal plane through the stereo image will be required. Knowledge of a horizontal reference is essential to surface assessment. The location of a horizontal plane in a given stereo image is dependent on four variables which may change from picture to picture: vehicle pitch and roll angles and camera pan and tilt angles. Requiring the operator to monitor and interpret these four separate pieces of information and to establish a horizontal reference mentally would be a difficult task and unnecessary burden on the operator if the vehicle is to operate on anything other than a smooth flat surface. A horizontal reference could be indicated by a pair of mutually perpendicular lines representing a horizontal plane. Alternatively, the horizontal reference might incorporate the characteristics of a scaling grid, if future studies discover a scaling grid that is worthwhile.

Probably the simplest method of generating the horizontal reference synthetic data is to produce a physical model representation of the horizontal reference and view it with optical sensors identical to those on the vehicle. The optical sensor would be mounted in a set of gimbals duplicating the necessary angular degrees of freedom. Video data from the sensors would then be mixed with the video data arriving from the vehicle. A disadvantage in this concept is the amount of space required for implementation. A full size model would be necessary to duplicate properly all the spatial cues in a stereo image. An alternate approach, for which a preliminary design exists, would be to generate the horizontal reference electronically through the use of electronic coordinate transformation and a flying spot scanner. Still a third method would be to generate the display information in a general purpose digital computer with a computer-operated electronic display (COED) generating the necessary lines in display coordinates. This latter approach would be very attractive for the operational system located at the SFOF. It may not be the best approach, however, if vehicle operation must be controlled from a location point where a large scale general purpose computer does not exist. This latter condition may exist during system development and testing or if the vehicle is to be controlled from one of the overseas DSIF stations. Actually this is a general problem confronting design of a computation system to handle on line computations necessary to support system testing and mission simulation. It is a problem which must be considered and solved early in the development phase.

A vehicle predicted path should be superimposed upon the surface images in order to permit the operator to quickly and accurately relate the geometry of possible vehicle paths to the geometry of the scene being viewed. Displaying a predicted path prior to committing the vehicle to motion would permit better planning of the subsequent course of action. Retaining a predicted path and updating its position as the vehicle moves into the field of view will permit achieving maximum step distances through closed-loop control. The main problem associated with implementing a predicted path is in ensuring that it is compatible with the geometry of the surface images over which it is superimposed. It is considered likely at the present time that proper geometric construction of a predicted path will have to consider the general contour of the surface as well as the camera and vehicle geometry. It is unlikely that an assumption of a flat surface will yield a predicted path in display space which is sufficiently accurate to be useful on anything but a generally flat surface. It may also be necessary to include such characteristics as surface texture and soil bearing strength in the mathematical model of vehicle dynamics necessary for path prediction computations.

Feedback information from the vehicle as it is moving indicating its current position and direction of movement is necessary to ensure that the vehicle is going where it was intended to go. This information has the maximum usefulness if it can be spatially related to the image of the surface, thus the requirement to overlay (plot) an actual path on the image of the surface. This information must be plotted in real-time as the vehicle is moving with an absolute minimum of ground processing delay. The ground processing delay should be no greater than one second from time of receipt of navigation data via telemetry to time of plotting a corresponding position. As with the predicted path, the actual path position in display coordinates should also involve consideration of the surface gross contour characteristics so that the path will be accurately related to the surface geometry.

A special case of path prediction, mainly prediction of the vehicle's position in operator time space, is necessary for effective closed-loop control. Prediction of the vehicle's present location in operator time space allows the operator essentially to ignore the existence of the transportation time delay in the control loop.

The Phase I ground operating equipment (GOE) concept provided for path prediction computations to be handled in one of the existing SFOF IBM 7090 computers. Experience with COED during this study indicates that this Phase I allocation of path prediction computations is probably not the best choice for an operational system. Vehicle dynamics simulated in the COED simulation were very simple. Even so, the combination of the number of points required to define a predicted path three-meters long plus the necessary iteration rate to provide a dynamic predicted path responding quickly to changes in operator's commands resulted in a sizeable computation load. Although these operations could undoubtedly be performed on the existing SFOF computer complex, these computations together with the necessary input/output communications for display generation of the predicted path would result in an inefficient use of that facility. Therefore it is recommended that consideration be given to a special purpose computer for predicted path commutations. The Phase I computation requirements for actual path and predicted path generation must be multiplied by two to generate these paths as a stereo image. Generation of the synthetic data would use a computer-operated electronic display device similar to the Bendix COED. If images are projected on a large viewing screen, then the synthetic data would be generated in a projection CRT and projected on the viewing screen in the same manner as the optical images of the surface.

4.3.10 References

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5. Murroughs, Thaddeus R., "Depth Perception---With Special Reference to Motion Pictures," J. SMPTE, Vol 60, Jun 1963, pp. 656-670.

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4.4 PLANIMETRIC DISPLAY REQUIREMENTS AND POSSIBLE IMPLEMENTATION

A planimetric display showing the present vehicle position, path history, and location of significant surface features and characteristics shown in symbolic form is considered highly desirable. The present vehicle position and previous track are easily produced via a computer controlled x-y plotter. The more difficult part of the problem comes in superimposing surface feature characteristics on this map in real-time as the mission progresses. It is suggested that this be accomplished by one or more special operators trained in photogrammetry and photointerpretation of the lunar surface. A special display would be provided for them in which a floating marker could be superimposed on the stereo images which would be displayed via optical separation. The floating marker control would be connected to a computer which would also receive the necessary reference data on the images being examined. The operator would then use the floating marker to outline features or areas of interest and the computer would provide the necessary coordinate transformation and plot outlines of these areas on the x-y map. Symbolic coding of the areas outlined would then be applied manually. If the plotter could be mechanized to plot on a transparent surface, then the computer controlled plotting head could be on one side while the photointerpretation symbolic coding is applied manually on the other without mutual interference. This arrangement would also permit a closed-circuit TV camera to view this map as it was being produced and continually updated. The map information could then be relayed by closed-circuit television to numerous other work stations in the ground complex where it is of interest.

4.5 NON-OPTICAL DISPLAY INFORMATION REQUIREMENTS

Non-optical display information requirements in support of vehicle remote control as derived from this study are listed in Table 4-2.

TABLE 4-2

NON-OPTICAL DISPLAY INFORMATION REQUIREMENTS FOR VEHICLE REMOTE CONTROL

Vehicle attitude, pitch and roll

Vehicle heading

Vehicle steering angle, or turning rate

Vehicle actual speed

Distance traveled from last stop point

Individual track speeds

Individual drive motor power (or current)

Relative bearing to destination

Distance to destination

Camera point angles

Camera f stop

Camera field of view

Critical vehicle and ground subsystems gross status indicators

Operating mode (from Mission Director)

4.6 COMMAND FORMATTING AND TRANSMITTION

An efficient, rapid, and automatic method of formatting and transmitting commands to the vehicle once a command decision has been made is essential for both safe and efficient control of the vehicle. Such a system is essential if mission time is to be minimized. This opinion was arrived at during the Phase I study and is still valid. All Bendix mission time estimates have assumed that such a system would be implemented. A detailed description of a command formatting and transmission system meeting these requirements is described in the Phase I final report. The essential features of this command formatting and transmission system are as follows:

1. The mission director authorizes a subordinate operator to generate commands within a certain category at the operator's discretion by operating a command formatter mode selection switch.

2. An automatic command formatter monitors the state of various control switches at each of several operator's consoles in accordance with the mission director's mode switch.

3. A direct electrical circuit from the automatic command formatter in the SFOF to the transmitter at Goldstone is provided.

4. An actual or fill-in command is automatically transmitted to the vehicle every one-half second. Fill-in commands are actually stop motion commands. Therefore if a command requiring positive motion is not received in a given one-half second interval at the vehicle, all mechanical motion is stopped. This applies to vehicle mobility, antenna movement, and camera movement.

5. Actual movement commands such as "move camera to the right" are repeated every one-half second for a total time period necessary to achieve the desired magnitude of movement.

6. Command words producing a parity error or containing an incorrect address are interpreted on the vehicle as "stop motion" commands.

There are no technical problems in implementing this command formatting and generation system, but it would require installation of a 48 bit per second data link from the SFOF to Goldstone. With this system command formatting time would not exceed the command sampling interval which for the Phase I design was one-half second.

4.7 CRITICAL GROUND ACTIVITY TIME ANALYSIS

The ground activity time analysis made in Phase I and reported in Section 13.6, Volume III of the Final Report has been revised and updated for Interpoint Driving Activity. Results are contained in Table 4-3. "Decision Time" which refers to all critical ground activity during the time the vehicle is stationary is essentially unchanged from the Phase I estimate of 2 minutes. Although display processing time and picture quality checks have been eliminated from the critical time path, the longer picture assessment time by the driver has made up for these reductions. No change in Intrapoint "Decision Time" would occur from the Phase I estimate of 3 1/4 minutes as a result of this study. It should be noted that changes in the vehicle communication subsystems to eliminate directional antenna pointing, antenna switching, and data mode (TM versus TV) switching would do more to reduce "Decision Time" than would reduction of picture evaluation time.

Times listed in Table 4-3 are optimistic but obtainable, as were those of the Phase I analysis. Both require the existence of a highly proficient and experienced operating crew and an efficient highly automated ground data processing facility.

TABLE 4-3

INTERPOINT DRIVING ACTIVITY (ALONG CRITICAL TIME PATH)

Category	Activity	Operator	Ground Time (sec)	Vehicle Time (sec)
Mode Change	Stop vehicle	Driver	-	-
	Signal step complete	Driver	3	
	Select antenna pointing mode	MD[1]	5	
			8	
Antenna Pointing	Compute required pointing angles and errors	Computer	2	
	Generate azimuth and elevation pointing commands	Computer	2	
	Antenna movement	–	-	6*
	Check new angles OK	Computer	2	
	Observe pointing complete	VSM[2]	2	
	Command antenna change	VSM	2	
	Monitor change and check data OK	VSM	5	
	Signal antenna ready	VSM	2	
			17	6
Mode Change	Select TV operation mode	MD	5	
			5	
TV Operation	Select TV pointing angles	Driver	5	
	Generate pointing commands	Computer	2	
	Camera movement	-	-	6*
	Check pointing OK	Computer	2	
	Observe pointing complete	VSM	2	
	Command TV Data mode	VSM	2	
	Check data sync OK	VSM	5	
	Command TV expose and transmit	VSM	2	
	Receive video (1 stereo pair)	-	2	19≠
	Evaluate picture and decide step to make	Driver	25	
			[illegible]	25
		x 1.8 pictures per step =	85	45
Mode Change	Signal ready to move	Driver	3	
	Select drive mode	MD	5	
			8	
Drive	Command vehicle movement	Driver	2	12 Δ
			2	12
		Total average time per step (for surface difficulty similar to that simulated in this study)	125	63

[1] Mission Director

[2] Vehicle Systems Monitor

* Assuming 30° azimuth plus 5° elevation required movement at 6°/sec

≠ 2 images at 8.5 sec each

Δ 4-foot step at average velocity of 4in/sec over random surface near mobility limit.

SECTION 5

NAVIGATION COMPATIBILITY

The choice of SLRV control system parameters may have some effect on the vehicle's ability to navigate. This section describes the effects of the control parameters chosen thus far for SLRV on the navigation system as described in the Phase I Final Report (BSR 903). The sensitivity of the navigation problem to a range of control system parameters is discussed. First, the significant interface points between the navigation and control subsystems are defined. Then, the performance requirements of both the navigation and control functions at these points are investigated.

5.1 NAVIGATION-CONTROL INTERFACES

The interfaces of information and equipment between the navigation and control subsystems are listed in Table 5-1 for both the vehicle and the ground operating equipment. Of the vehicle equipment, all the major components of navigation hardware are listed with the exception of the RF ranging equipment. In addition to the components described in Phase I, vehicle steering readouts will be required and were added to the interface list.

The RF ranging equipment was omitted as an interface point because it is not directly used for vehicle control information. This equipment could give a very accurate measure of vehicle travel, but only when the SLRV is traveling radially with respect to the Surveyor spacecraft. It is recognized that the RF ranging equipment will be highly useful in calibrating the vehicle odometer, but this would not constitute a first-order effect on control performance.

During Phase I, the requirement for a readout of vehicle steering or articulation angle was considered but was not established as a necessity. Experience in driving the ETM on the test course has indicated that knowledge of the vehicle steering angle is a requirement for closed-loop control of the vehicle. Without this information, knowledge of the vehicle's path in a turning maneuver is extremely poor.

TABLE 5-1

NAVIGATION-CONTROL EQUIPMENT AND INFORMATION INTERFACES

VEHICLE

- TV Sensor Optics, Gimballing, and Pickoffs
- Odometer
- Inclinometer
- Sun Sensor
- Steering Readouts

COE

- Driver Display Data
- Planimetric Display

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The navigation-control interfaces in the ground operating equipment are primarily those of information flow; that is, navigation readouts and/or computed values transferred to the driver control console for the driver display.

5.2 SENSITIVITY OF NAVIGATION TO CONTROL PARAMETERS

5.2.1 TV Sensor, Optics, and Gimbaling

In Phase I, a requirement was established for a longer focal length television lens to be used in the transit mode of operation of the television. The field of view of this lens was established as equal to or less than $22\text{-}1/2^{\circ}$. For effective vehicle control, it appears that a field of view equal to or greater than 70° will be required. Although this is greater than the 50° value estimated during Phase I, the difference in requirements does not add any new mechanization problems to the vehicle since a need for two different fields of view was recognized in Phase I.

In the transit mode of operation of the television, a high picture resolution is advantageous. Partially for this reason, it was decided in Phase I that a resolution capability of 512 by 512 picture elements was required. The interim study shows that for fine textured terrain, high resolution is needed to form a good stereo model. In cases of very fine texture and very small terrain relief, even 512 square picture elements would not be sufficient. On the other hand, it appears that for a surface of gross texture and relatively high relief, this resolution is not required. Therefore, the 512 by 512 element resolution determined in Phase I will be adequate for all surfaces except those of very fine texture and very low relief. On surfaces of greater relief, a degraded picture resolution mode should be sufficient to form an adequate stereo model.

A required gimbal authority of $\pm 200^{\circ}$ of azimuth and plus 15° minus 60° in elevation was determined in Phase I. From driving experience with the vehicle, these values appear adequate.

The transit mode of operation of the television imposed the minimum gimbal readout accuracy of $\pm 1/4^{\circ}$. This accuracy appears more than adequate for vehicle control.

5.2.2 Odometer

The dead-reckoning mode of navigation established a requirement for a vehicle odometer with a 2% accuracy over a smooth terrain with a coefficient of friction of 0.6. Experience in driving the ETM and the results of the terrain assessment test program indicate that for control purposes an odometer accuracy of ±10% would be sufficient. Since this is less than the standard deviation of distance-to estimates, it would not noticeably increase any safety factors which might be applied to vehicle's step length. However, this accuracy must be obtainable on all surface types within the limits of vehicle mobility to provide effective control of vehicle step lengths.

5.2.3 Inclinometer

The Phase I inclinometer design called for a measuring range of $\pm 30^{o}$ and a worst-case static or dynamic error of ±10 (arc) minutes. For navigation purposes and to eliminate the small surface variations it was desired to keep the inclinometer natural frequency as low as possible, ideally about 0.03 cycles per second. To simplify on-board vehicle equipment, it was decided to accept an inclinometer natural frequency of 1 cycle per second sampled at a high frequency rate and reduced by ground data processing to a response equivalent to a very low natural frequency.

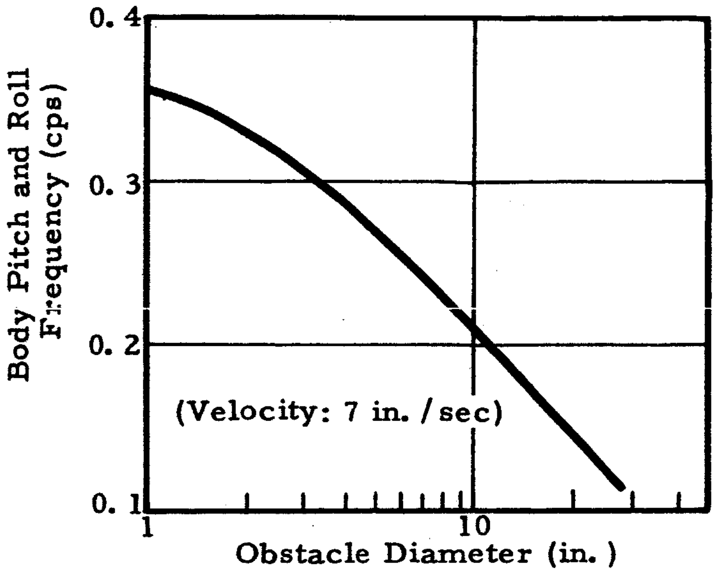
The combination of a relatively high inclinometer natural frequency and a high telemetry sampling rate satisfies the inclinometer requirements established by vehicle control. Figure 5-1 plots the LRV roll and pitch body frequency as a function of obstacle diameter for the maximum vehicle linear velocity (7 inches per second). Even with obstacle diameters as small as 1 inch, the body frequency never exceeds 0.4 cycles per second. It appears that a one cycle per second natural frequency is adequate for control purposes.

For vehicle safety and driver display or feedback for closed-loop control, it appears that a worse case error of one to two degrees is sufficient.

To account for extreme driving situations, the inclinometer range should extend to the limit of vehicle stability, at least in the roll axis. The stable range of pitch angles is so large that failure in this mode is a remote possibility.

Figure 5-1

PITCH & ROLL FREQUENCY VS OBSTACLE DIAMETER



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5.2.4 Sun Sensor

The requirement of measuring vehicle azimuth for the dead-reckoning navigation system established a sun sensor accuracy of $\pm 1/2^{\circ}$ of a hemispheric field of view. This performance appears more than adequate for vehicle control.

5.2.5 Steering Angle

As mentioned above, no firm requirement was established in Phase I for a readout of vehicle steering or articulation angle.

The vehicle control function, if it is to be accomplished in a closed-loop manner, requires a readout of the vehicle steering or articulation angle. This information is required to correct for vehicle understeering or oversteering due to interaction of the vehicle tracks with the terrain surface. Lack of this information causes an objectionable uncertainty in vehicle path during a turning maneuver and would consequently require shorter step lengths while turning. A readout accuracy of 1° to 2° appears more than adequate.

5.2.6 Driver Display Data

The following data are required for the vehicle driver's display, either directly from the on-board vehicle sensors or from the ground navigation computations: (1) vehicle roll and pitch, (2) camera inertial pointing angles, (3) bearing to destination, and (4) vehicle steering angle.

In addition to these individual data, a planimetric path display should be provided, which would assist in controlling the vehicle while backing for short distances or driving over any previous traverse. In addition, the display may prove useful in monitoring control performance and modifying control safety factors during the course of a mission. The display would be constructed primarily from navigation system data supplemented by limited photogrammetry and photo-interpretation of the TV images for location and classification of particular obstacles.

5.3 CONCLUSIONS

The navigation subsystem as defined in the SLRV Phase I Final Report is not adversely affected by the choice of the control system parameters generated by this study. In all cases the critical performance requirements established for the navigation sensors in Phase I exceed the requirements for control except in the case of the odometer and steering readouts.

APPENDIX A

ETM TEST EQUIPMENT

The following equipment is required for an SLRV ETM operational control system but was not delivered to JPL under the provisions of this study contract. This list includes equipment required for conducting a vehicle remote control test program.

1. Two Sylvania Series 880 high-resolution closed circuit TV cameras. The vidicon was replaced with a separate Mesh Vidicon (Type 1355). A standard vidicon camera control unit with internal sync was modified to drive a second vidicon camera as a slave unit.

2. A Sylvania Model No. 21TCEU color TV receiver was modified by the addition of two channels of video amplification. Separate brightness and contrast controls were provided for each video channel. (NOTE: Modification to the TV cameras and receivers were made by Sylvania Home Appliance Division, Batavia, New York.)

3. Video and power cables were provided to allow use of the vidicon camera units up to 50 ft from the camera control units. Cables 150 ft long were provided to connect the vidicon control units with the TV receiver.

4. A Pelco Sales Inc. Model PT-155S light-duty pan-tilt accessory was mounted on the ETM to provide TV camera servo control.

5. A Pelco Sales Inc. Model PT-1500 control unit was used to provide an operator remote servo drive unit and pan and tilt angle readouts.

6. The following lenses were used during the study:

   2 each - Kintel, Model AL-1A

   2 each - Kintel, Model AL-2A

   2 each - Kintel, Model AL-14